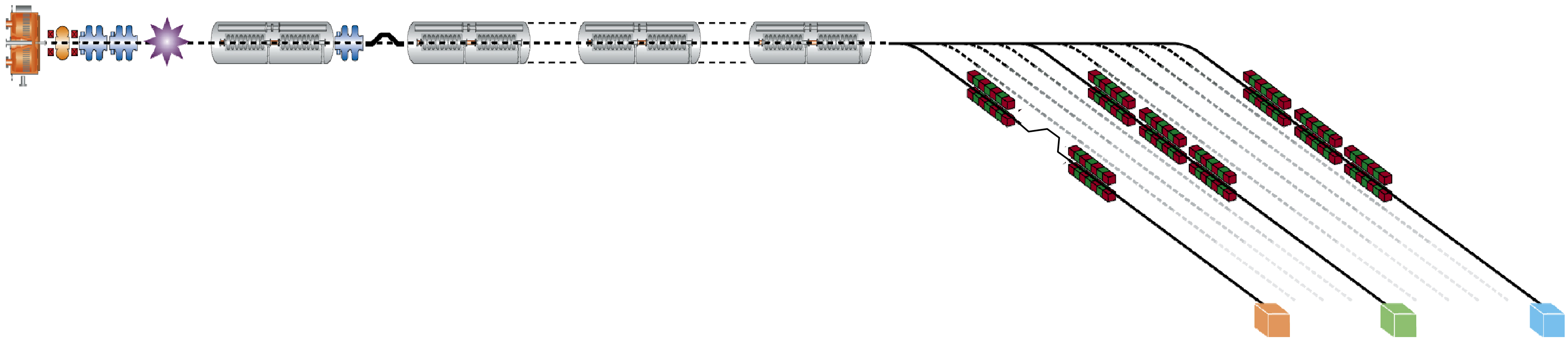
Overview of X-Ray FEL R&D at LBNL



John Corlett
For the Next Generation Light Source Team
Mini-workshop on the Compact X-ray FELs Using High-Brightness Beams
LBNL
August 6, 2010

Source Requirements for a New Light Source in the Soft X-Ray and VUV

Tunable X-rays

Elemental specificity, spatial resolution, penetrating power, inner-shell atomic physics

~100 eV – 1 keV
harmonics to 5 keV

High Repetition Rate

High average X-ray power without sample damage
Signal averaging

10-100 kHz
1-100 MHz possibility
Watts to 10's Watts X-ray power

Ultrafast Time resolution and Synchronization

Required for all dynamics studies
Freezing atomic motion, femtosecond dynamics

250 as – 500 fs pulses

Controlled, intense pulses

Single-shot applications, nonlinear effects
Limit flux/pulse
Avoid sample damage

50 µJ in 50 fs = 1 GW
50 µm focus = $4x10^{13}$ W/cm^2

1 µJ in 50 fs = 20 MW
50 µm focus = $8x10^{11}$ W/cm^2

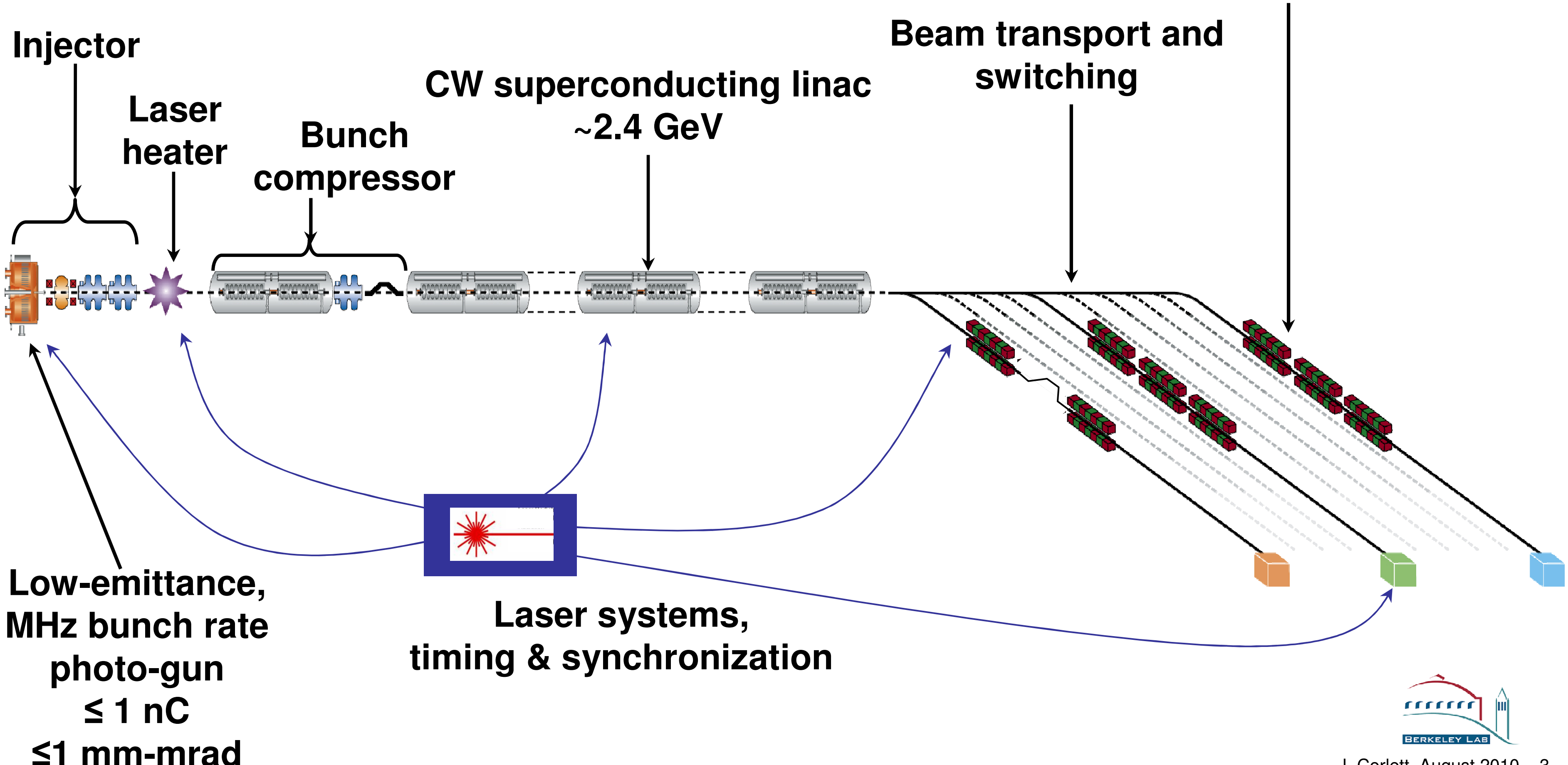
Coherence

Monochromatic source
Transverse coherence for small focus
High degeneracy ($N_{photons}$ per optical mode)

Close to Fourier transform limit

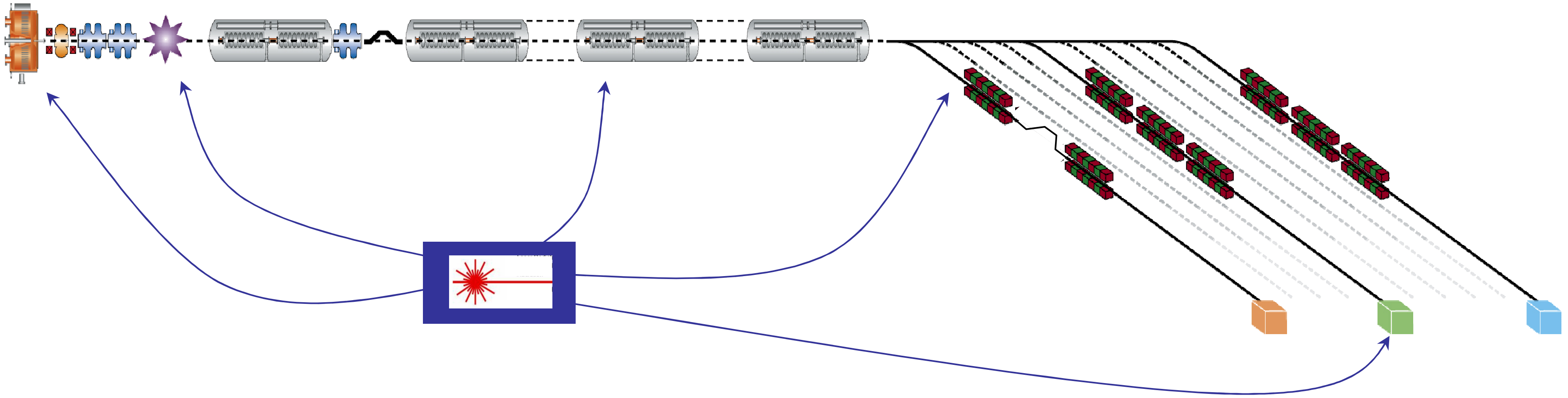
Concept for a High-Repetition Rate, Seeded, VUV–Soft X-ray FEL Facility

Array of 10 configurable FEL beamlines, up to 20 X-ray beamlines
100 kHz CW pulse rate, capability of one FEL having MHz rate
- Independent control of wavelength, pulse duration, polarization
- Each FEL configured for experimental requirements;
  - seeded, attosecond, ESASE, mode-locked, echo effect, etc



LBNL R&D goals

Develop a credible machine pre-conceptual design
Develop technologies to reduce risk and costs
Build expertise and demonstrate competence in critical technologies

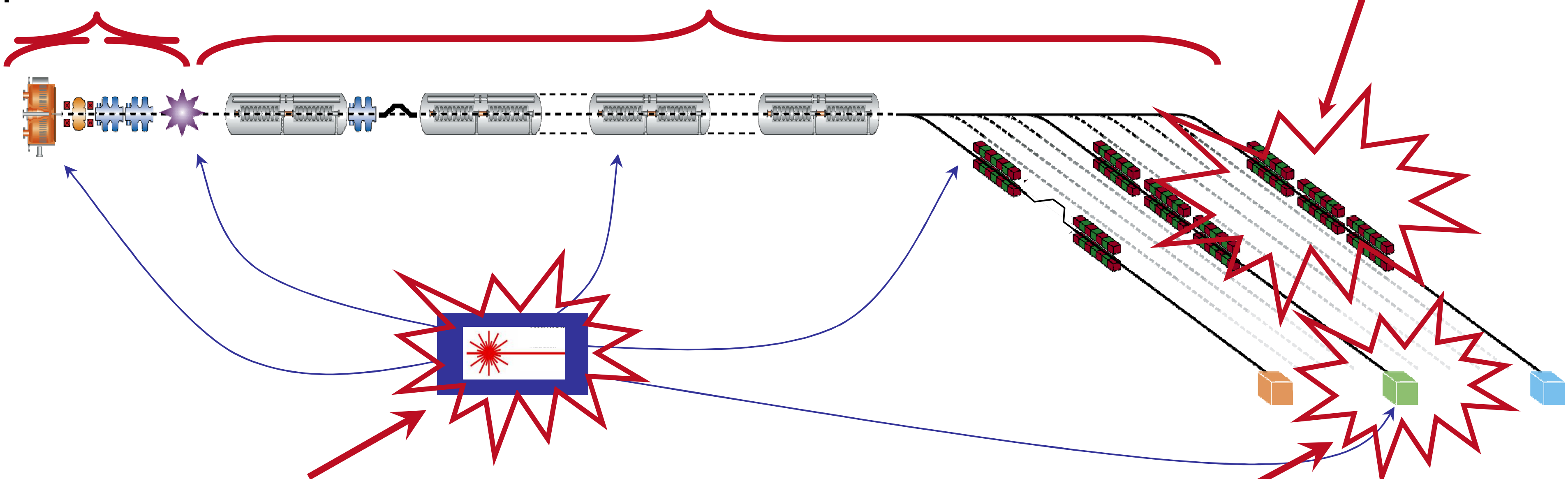


LBNL R&D activities

Production and manipulation of electrons for optimal X-ray production

Beam delivery to accelerate and transport high-brightness and high-power beams to the FELs

FEL designs and technologies for control of X-ray output



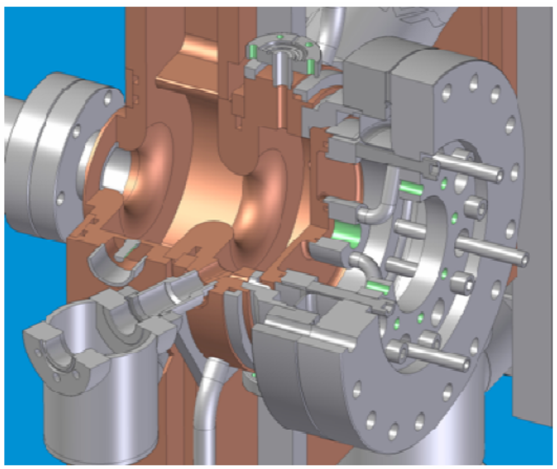
Laser systems for seeding, optical timing & synchronization

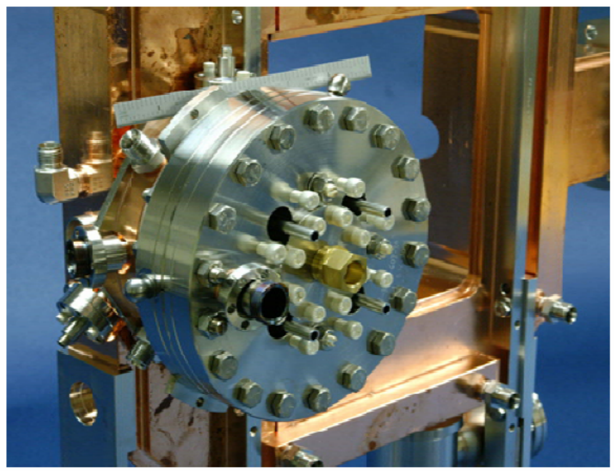
High frame-rate detectors

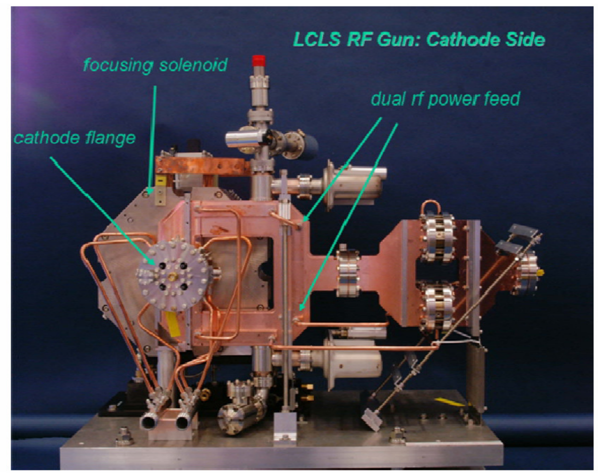
High quantum yield multi-alkali cathodes for psec pulsed electron sources

LCLS uses a state of the art RF photo-injector
- Large frequency tripled Ti:Sapphire laser + copper cathode

NGLS photo-injector needs to operate at 10,000 x the repetition rate
- Laser scaling not possible





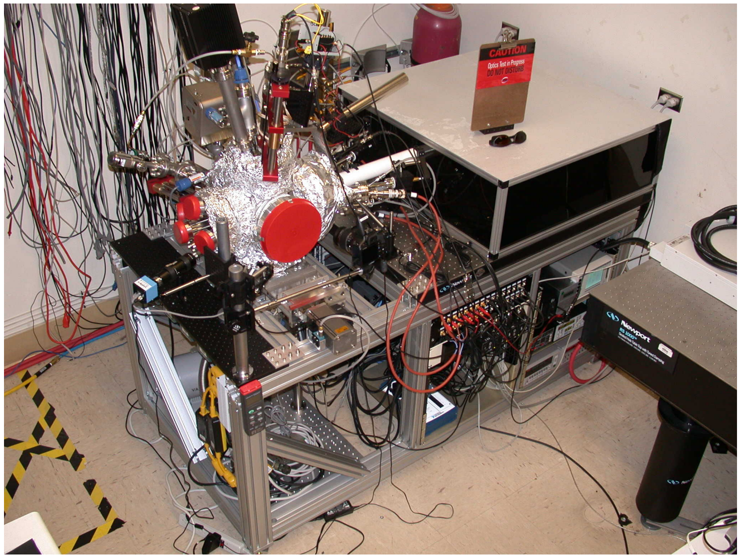


- NGLS requires ~ 10,000 x higher efficiency photocathode with same or lower emittance

Latest results with antimonide deposition system

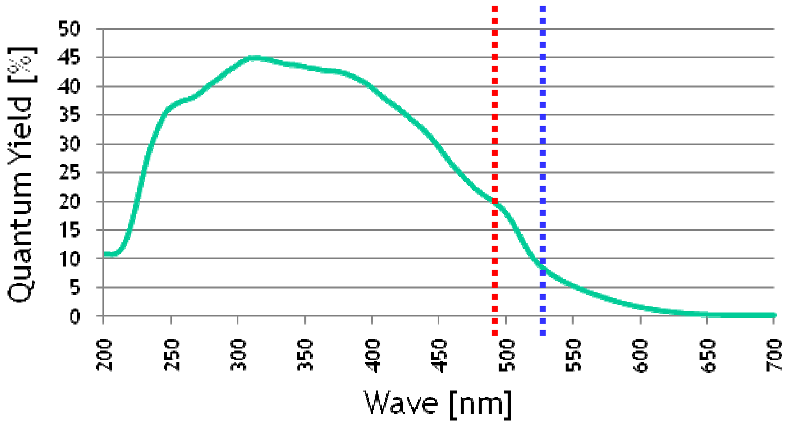
Choice of material K_2CsSb

- ~ 10 % in the green
    - Enables use of simple fiber lasers
- Requires good UHV (low H_2O partial pressure)



Very high QE achieved in new deposition system

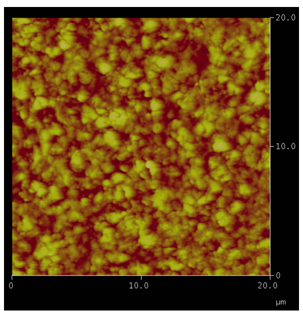
20 % QE 496 nm including accelerating field
8% QE at zero field



- Computer controlled MBE chamber
- Laser plasma UV-visible source
- Very rapid in situ QE monitoring
- Special rapid heat / cool stage

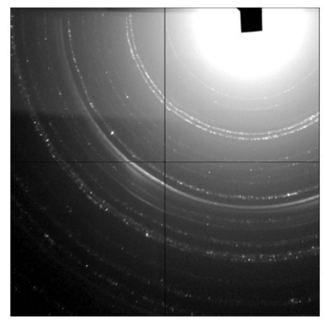
Latest results on alkali antimonides

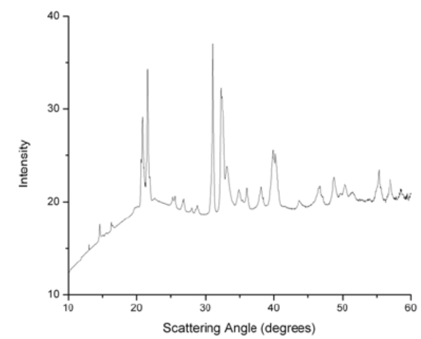
- Enables use of small, very efficient, low power turn key fiber lasers
    - 1 MHz, 1μJ (1064 nm), 0.5μJ (532 nm), 500 fsec
    - 300 x 200 x 100 mm laser head

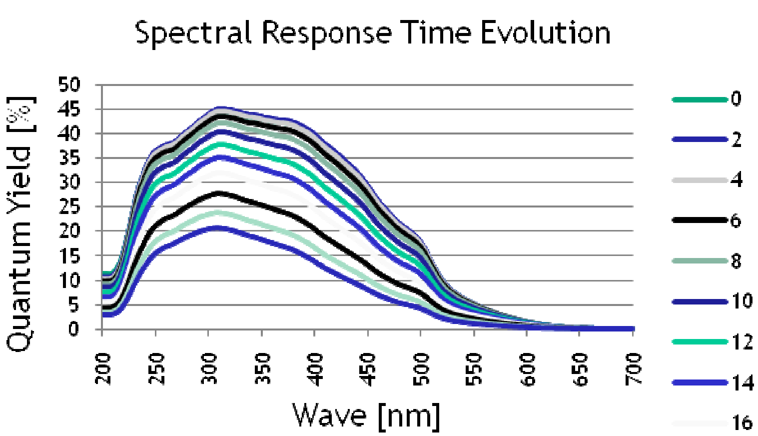


- AFM shows 50 nm roughness
    - might affect emittance in a high gradient field

- Initial grazing diffraction from alkali antimonide

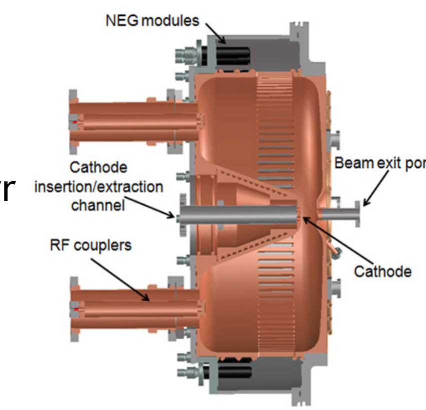




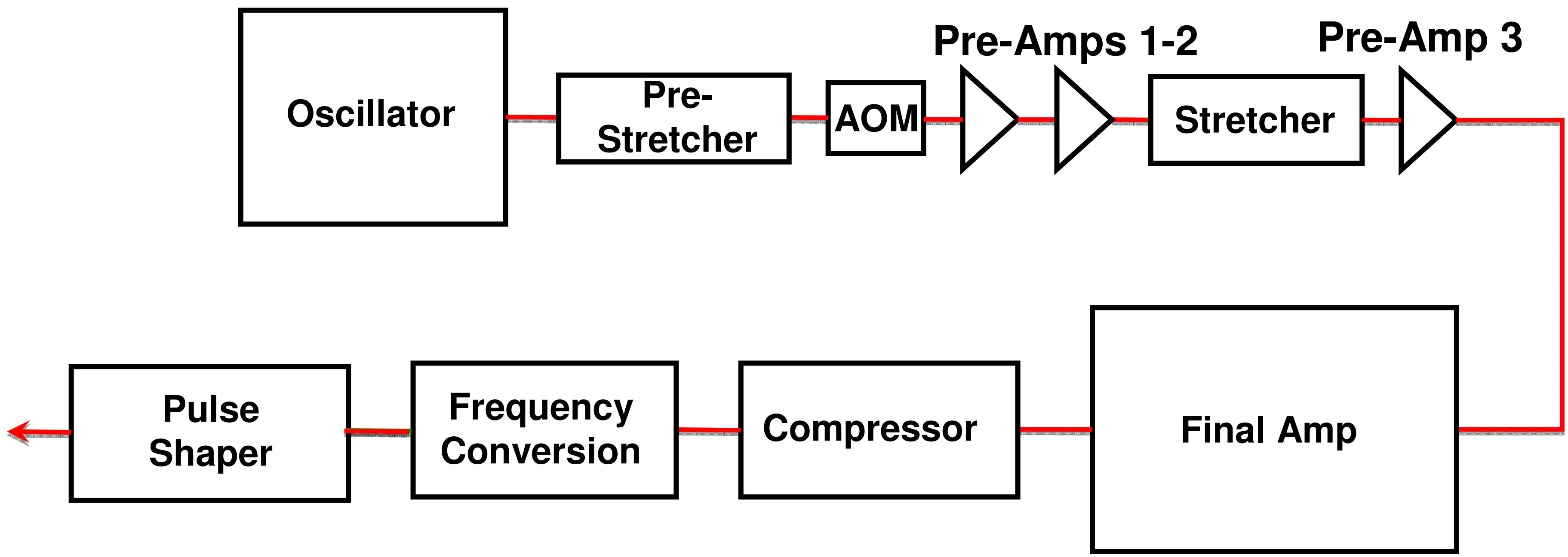


- 18 hr lifetime at ~10^{-9} mBar
- Need low partial pressure of H_2O
- Investigating capping layer

- LBNL VHF gun is designed for 10^{-11} Torr



Photocathode Laser (1)



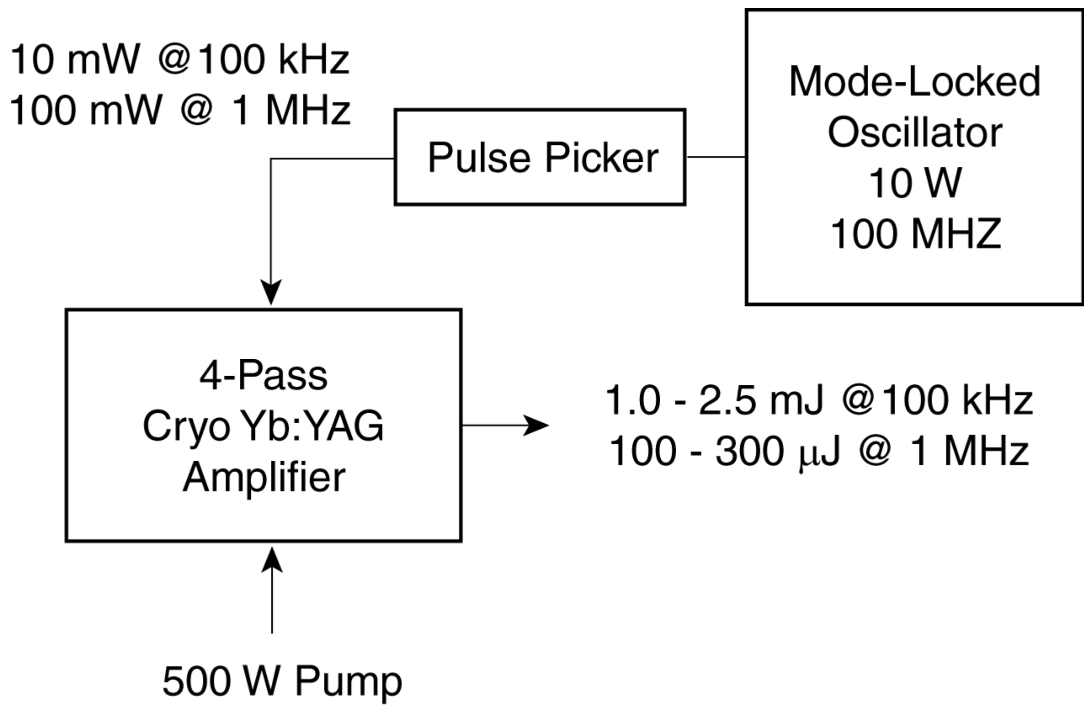
Lawrence Livermore National Laboratory

Built by LLNL

1 MHz
1 mJ @ 1064 nm (1 W)
~0.4 mJ @ 532 nm (0.4 W)
~1 ps FWHM

Photocathode Laser (2)

Built by Q-Peak and MIT-LL

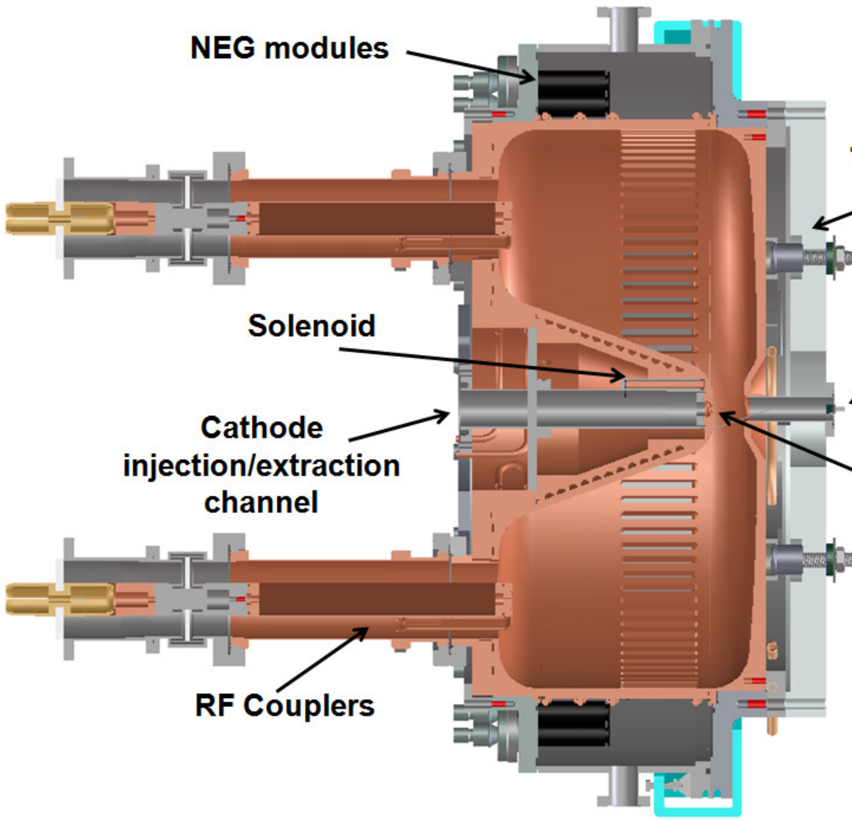


0.1 mJ per pulse

100 to 300 W!

- **Passively mode-locked cryo Yb:YAG laser**
- **Use a pulse picker to reduce the repetition rate to as low as 100 kHz**
- **Amplify the resulting pulse train in a 4-pass cryo Yb:YAG laser**

A High Rep-rate VHF Cavity Electron Gun



Simultaneous requirements for a NGLS electron source:

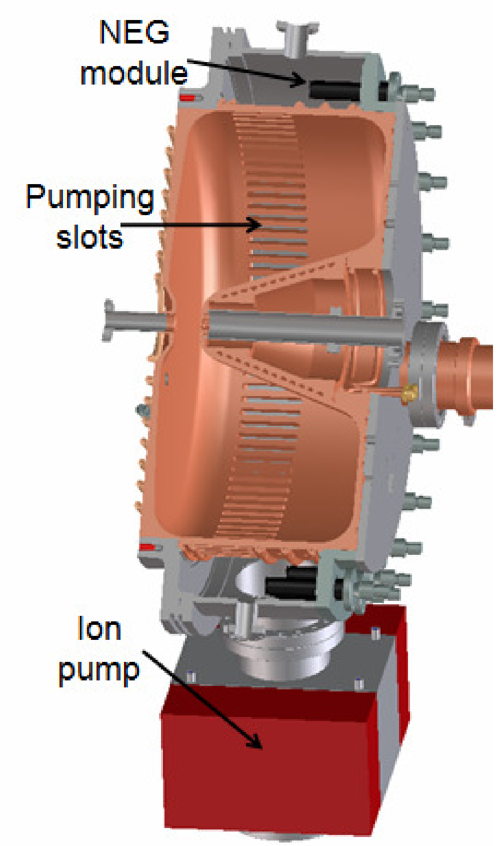
- Repetition rates of up to ~ 1 Mhz
- Sub 10^{-6} m normalized beam emittance
- Compatibility with magnetic fields at the photocathode
- Variable bunch length for controlling space charge effects
- Final beam energy > 500 kev with gradients > 10 MV/m
- Charge per bunch up to ~ 1 nc
- “Easy” installation and test of different kind of cathodes
- 10^{-11} torr vacuum capability

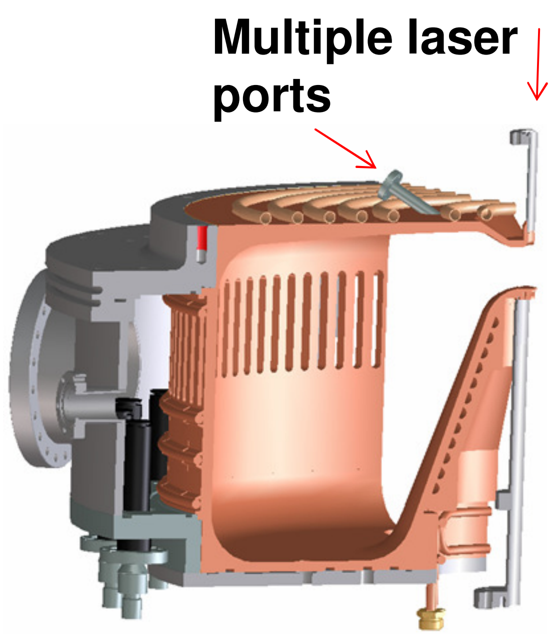
J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

K. Baptiste, et al, NIM A 599, 9 (2009)

A High Rep-rate VHF Cavity Electron Gun

UHV systems



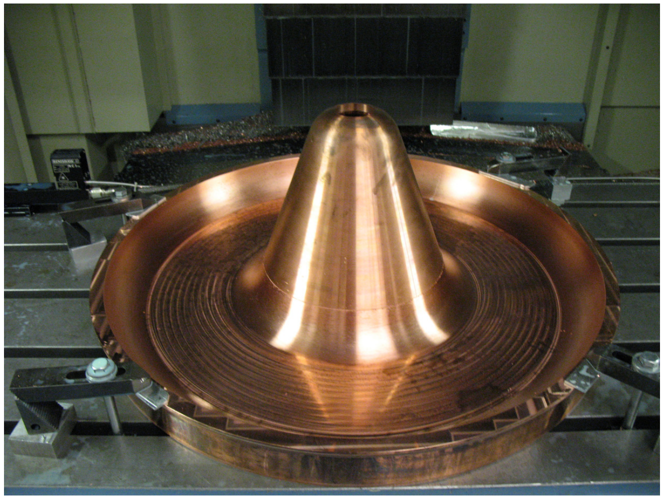


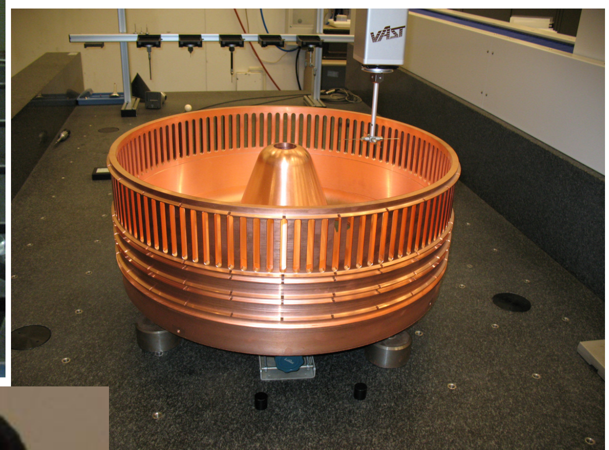
Frequency	187 MHz
Operation mode	CW
Gap voltage	750 kV
Field at the cathode	19 MV/m
Q_0	30887
Shunt impedance	6.5 MΩ
RF Power	90 kW
Stored energy	2.3 J
Peak surface field	24 MV/m
Peak wall power density	25 W/cm²
Accelerating gap	4 cm
Diameter/Length	70/35 cm
Operating pressure	< 10^{-11} Torr

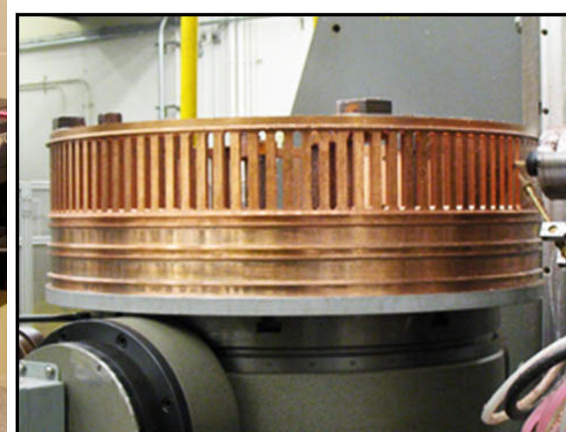
J. Staples, F. Sannibale, S. Virostek, CBP Tech Note 366, Oct. 2006

K. Baptiste, et al, NIM A 599, 9 (2009)

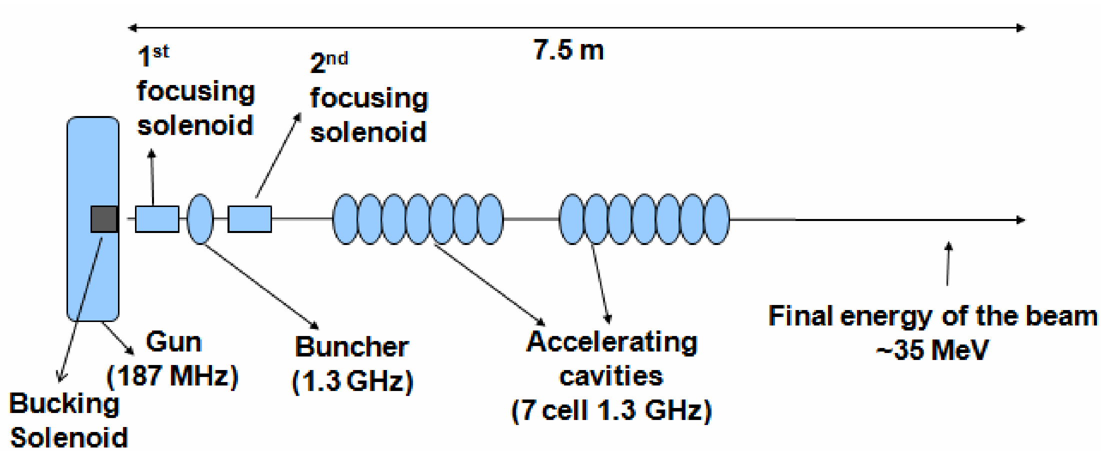
VHF Gun Cavity Fabrication

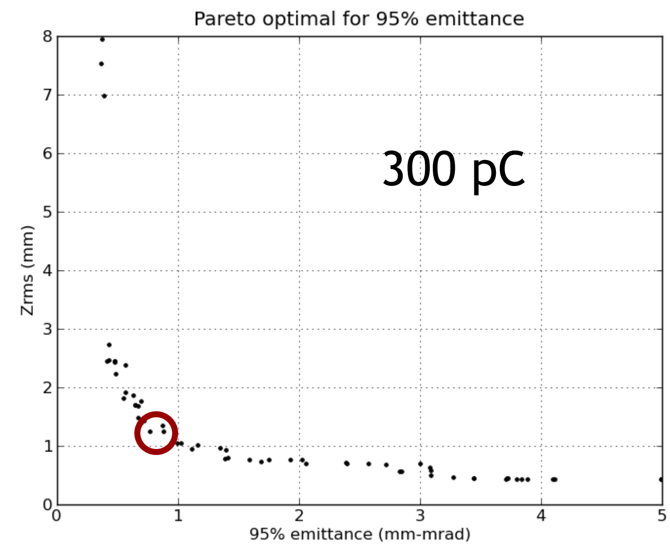


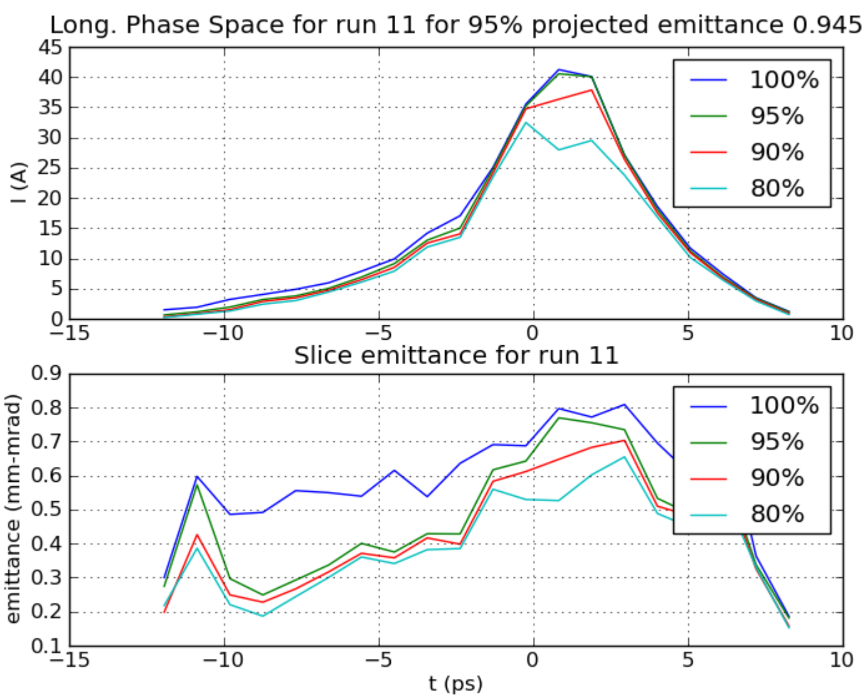


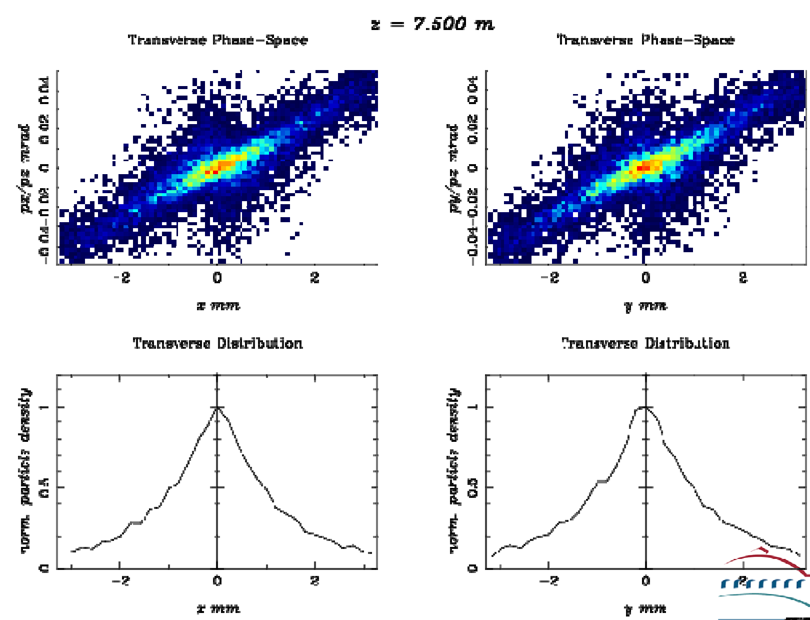


Injector beam dynamics



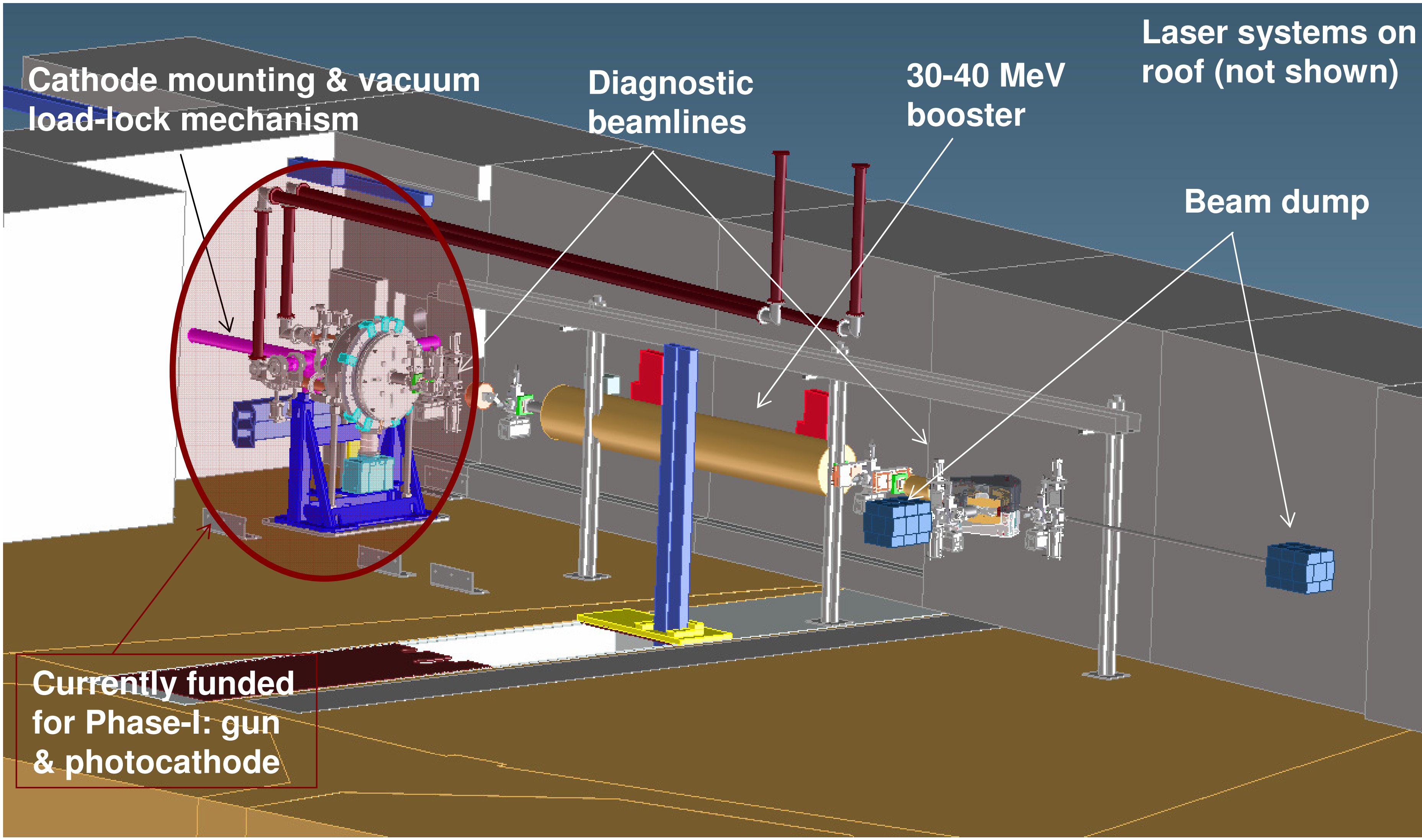






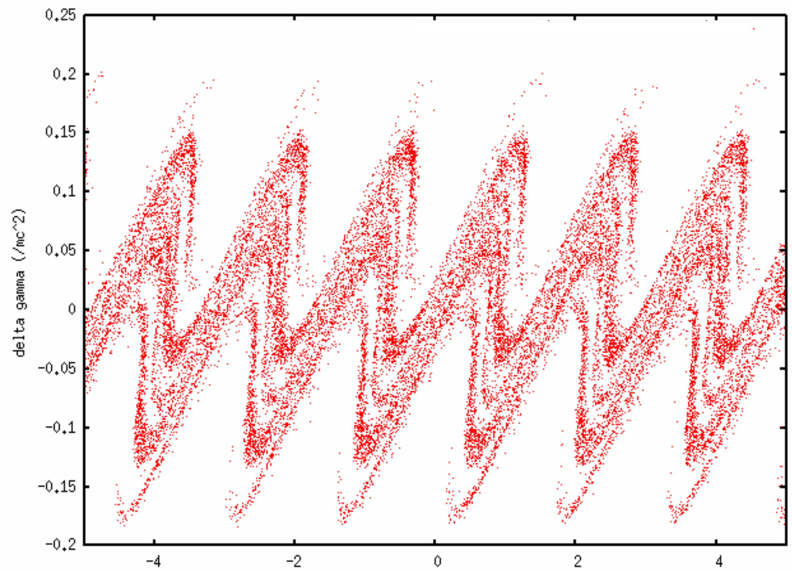
APEX
Advanced Photoinjector EXperiment

- RF, Gun, Cathode, & Laser tests in the ALS Beam Test Facility (BTF)
- Cavity RF conditioning planned for late summer



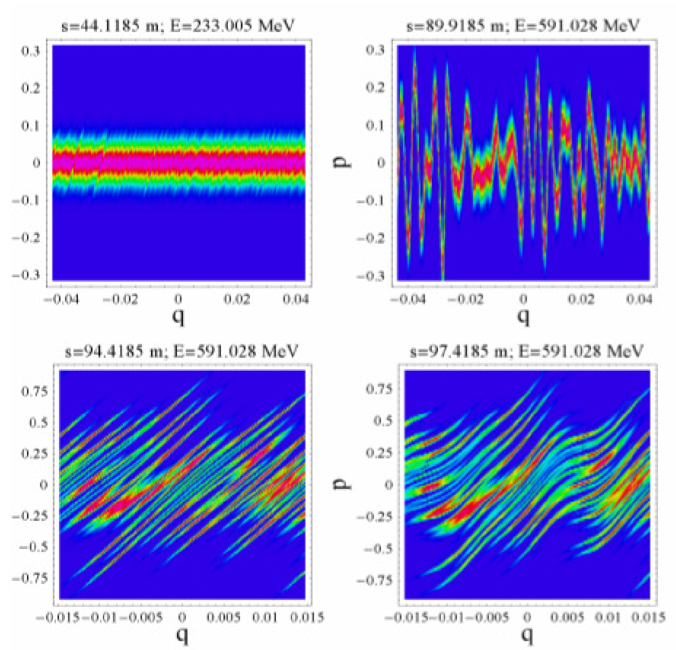
Multi-physics, high resolution modeling

Longitudinal phase space at the end of echo chicane



Position along bunch (μm)

Evolution of longitudinal phase space in chicanes



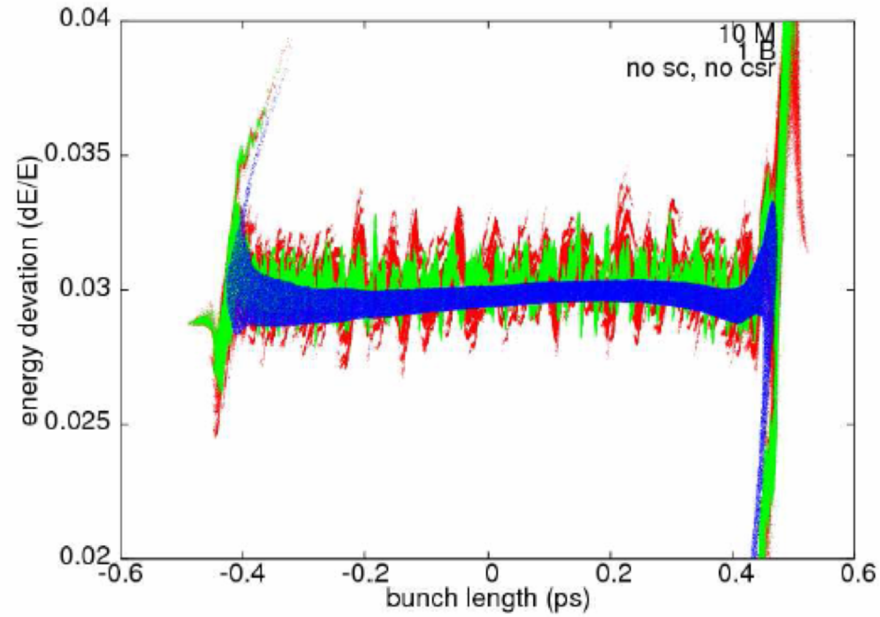
- Large scale high resolution (e.g. 5 billion macroparticles) is needed in order to resolve the fine structure (sub micron) in the echo seeding scheme and the laser heater anomalous trickle heating
- Multi-scale resolution in parallel beam dynamics simulation will help significantly lower the computational cost

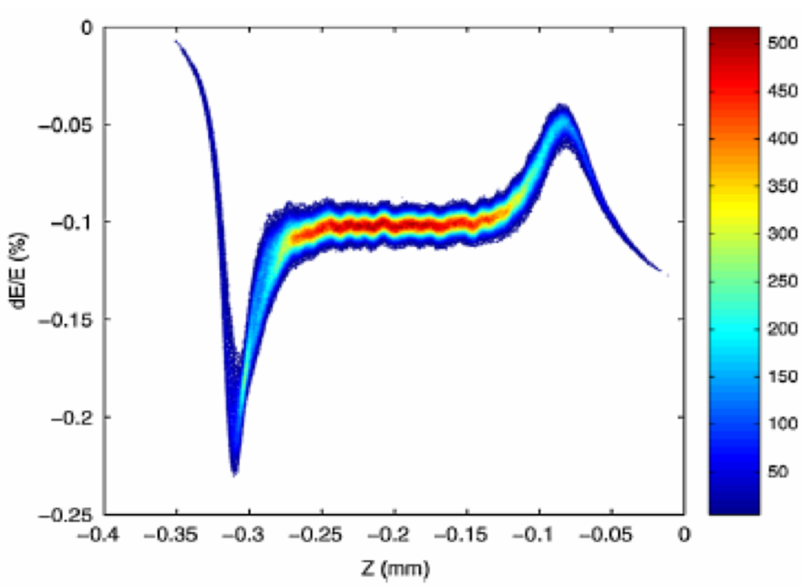
J. Qiang, R. D. Ryne, M. Venturini, A. A. Zholents, I. V. Pogorelov "High resolution simulation of beam dynamics in electron linacs for x-ray free electron lasers," Phys. Rev. ST Accel. Beams, 12, 100702 (2009)

Multi-physics, high resolution modeling

IMPACT simulations of the longitudinal phase space

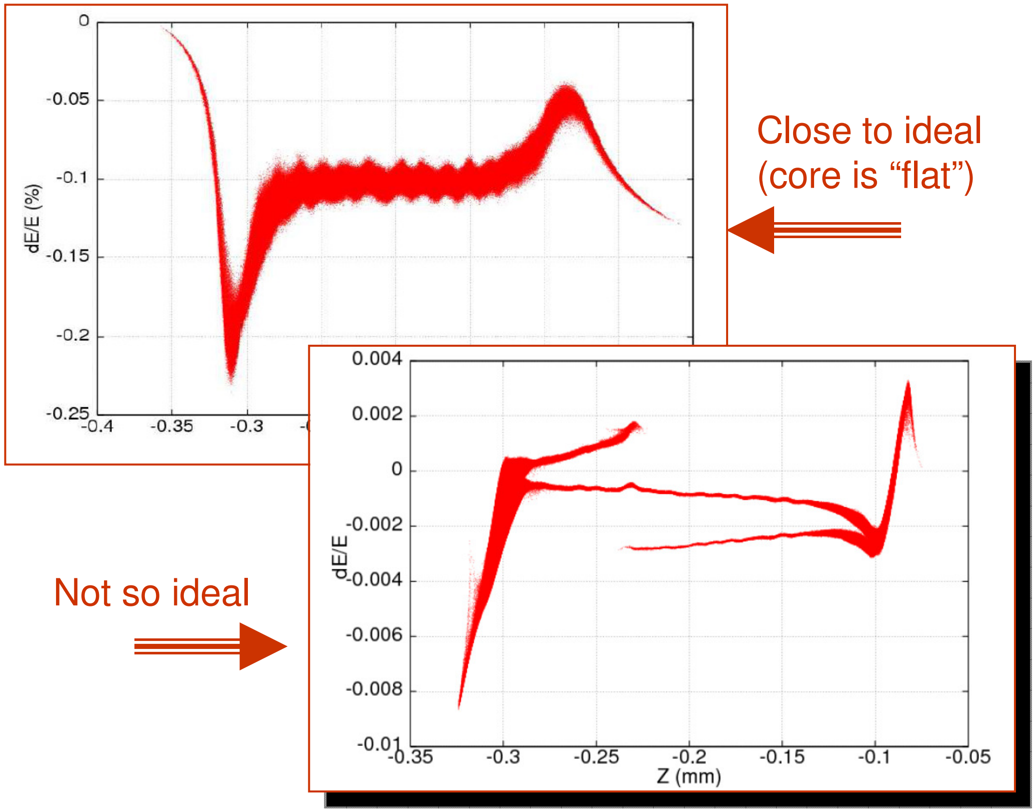
- **Collective effects are neglected (blue)**
- **Collective effects included (green, red)**
- **Simulations with one billion macroelectrons (green)**
- **Simulations with 10 million macroelectrons (red)**





Density plot for a beam distribution with *5 billion* macroelectrons

Develop methods to control the phase-space of beams

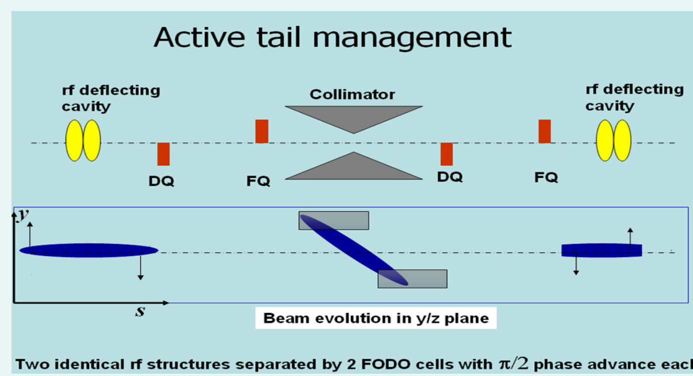


Close to ideal (core is "flat")

Not so ideal

- Limit variations of electron energy along the bunch
- Demonstrated a solution for high-charge (0.8nC) long (500fs) bunches exploiting wake-fields from rf structures [LBNL-26706-E (2009)]
- Lower charge bunches are more problematic (rf wakes not as strong)
  - Explore novel remedies (high permittivity material insertion generating controllable wakes)
  - Examine feasibility of more traditional solutions using rf structures. Evaluate trade-offs

- Electrons in the longitudinal tails of beam distribution may have to be removed to avoid uncontrollable losses.
- We have proposed a novel device to accomplish the task [LBNL-26706-E (2009)]
- Conceptual design needs to be followed by detailed simulations to verify performance, feasibility

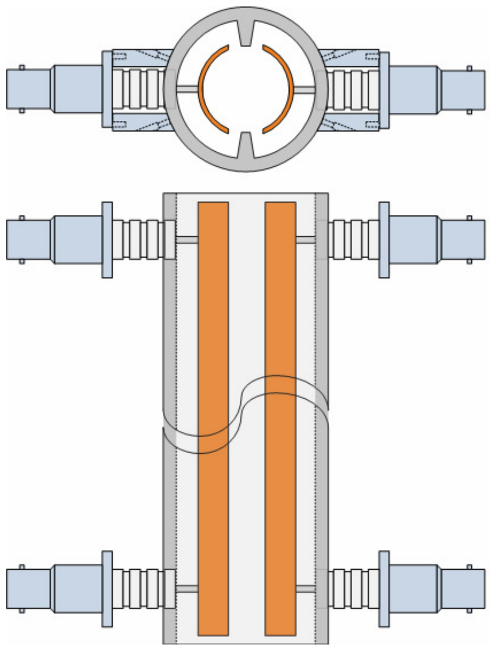


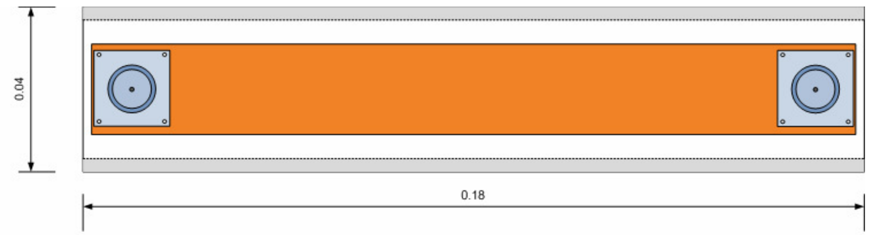
Fast kicker and pulser

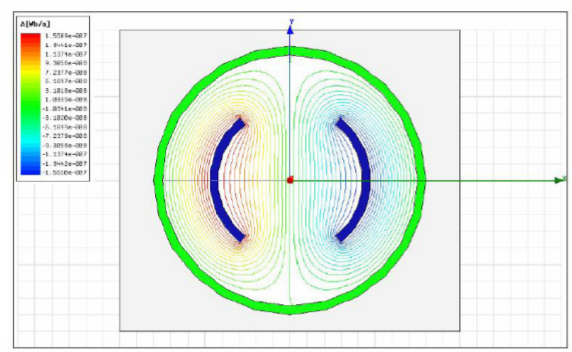
•Design, construction and test of a high repetition rate fast kicker and pulser

- Demonstrate reliable operation at the required field quality and shot to shot stability

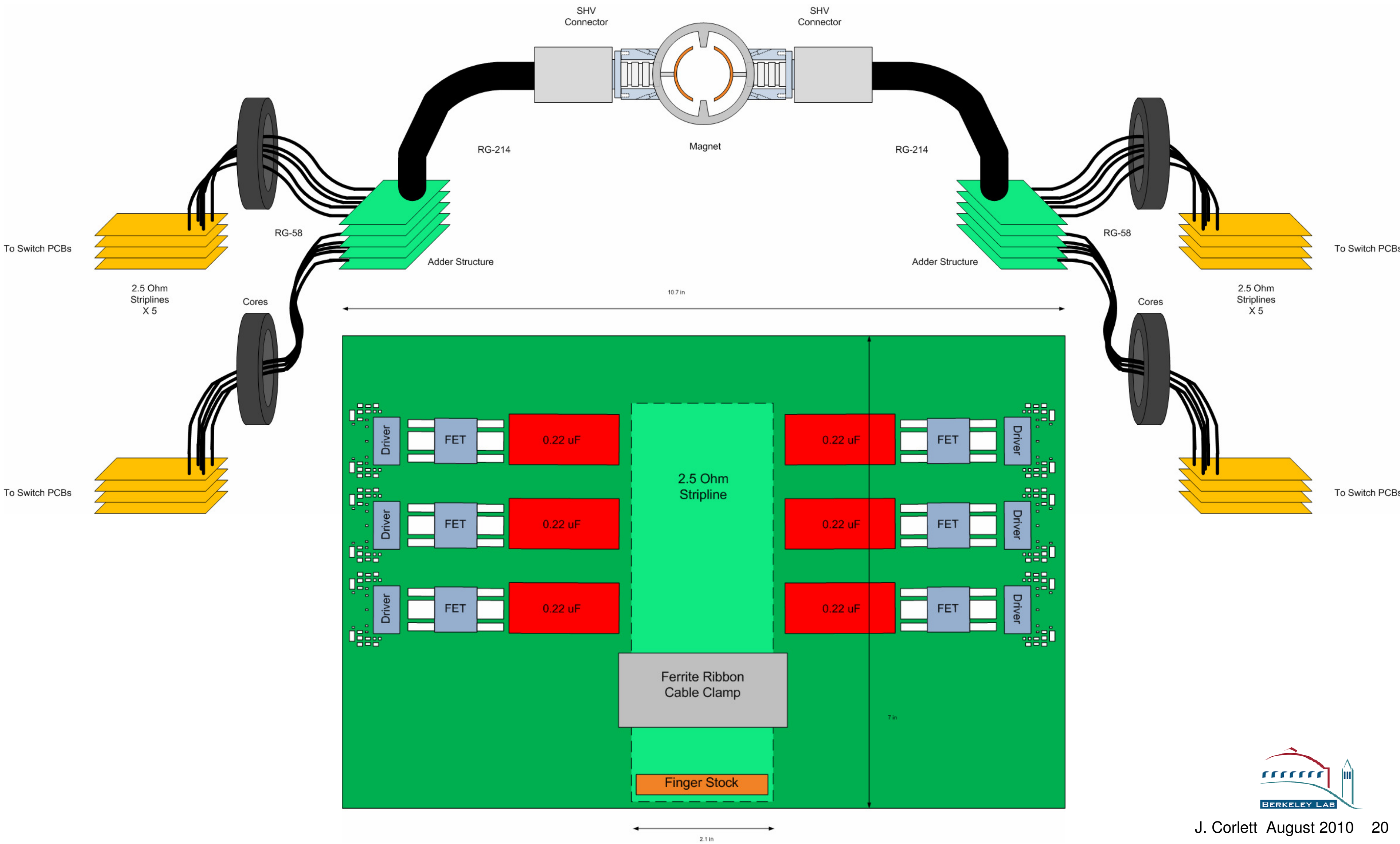
Beam Energy	2.4 GeV
Bend Angle	3 mrad
Magnet Length	2 m
B Field	60 G
E Field	1.8 MV/m
Aperture	17 × 17 mm
Rise/Fall Times	5 ns
Pulse Width	10 ns
PRF	100 kHz







Transmission line adder pulser



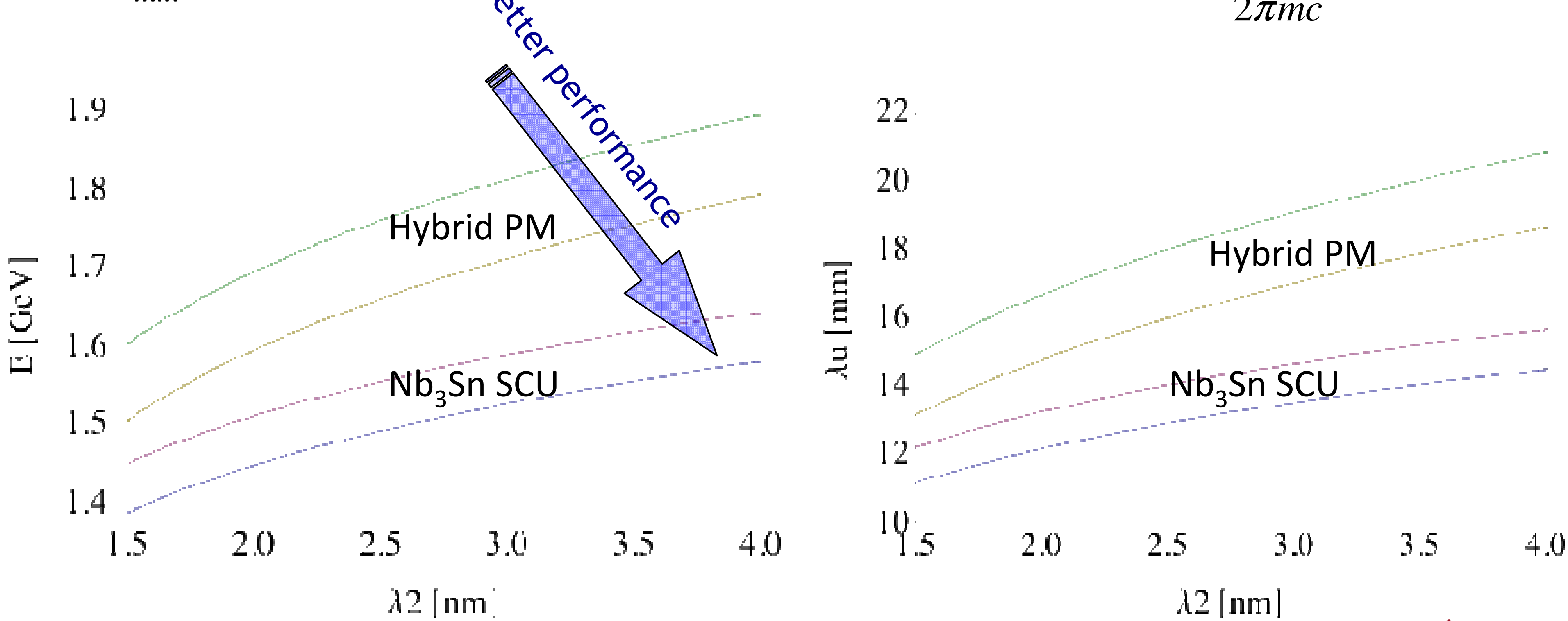
Development of undulator technology can have great impact on machine size and cost

Short-period undulators to radiate at lower energy

- **1-4nm tunability**
- **5.5-6.5mm magnetic gap shown**
- **K_{min}=0.8**

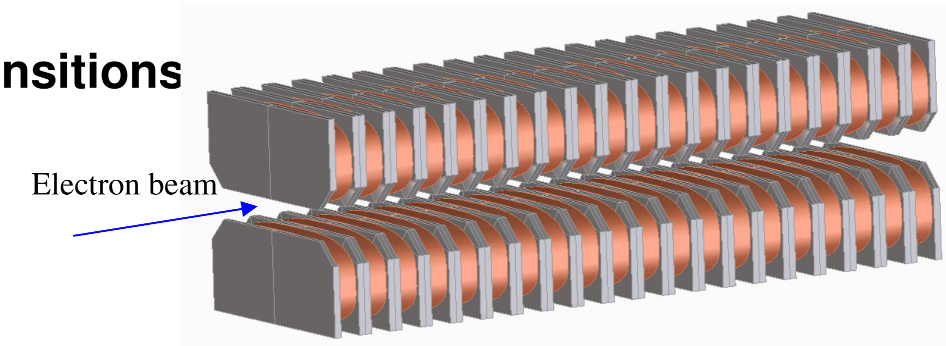
$$\lambda_{x-ray} = \frac{\lambda_{undulator}}{2\gamma^2}\left(1+\frac{K^2}{2}\right)$$

$$K = \frac{eB_0\lambda_{undulator}}{2\pi mc}$$

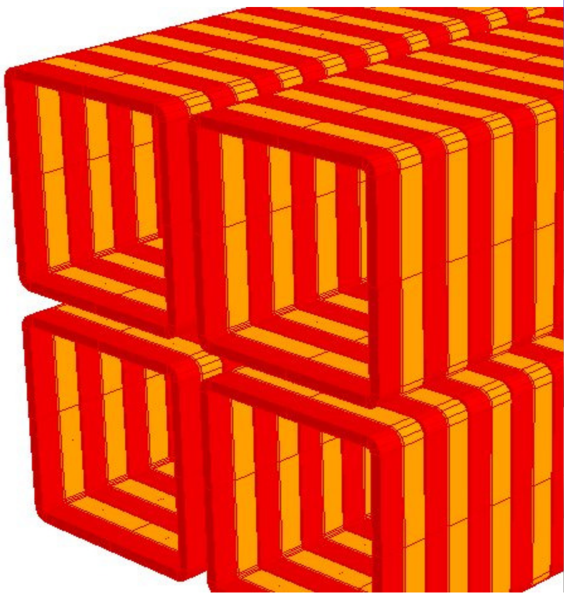


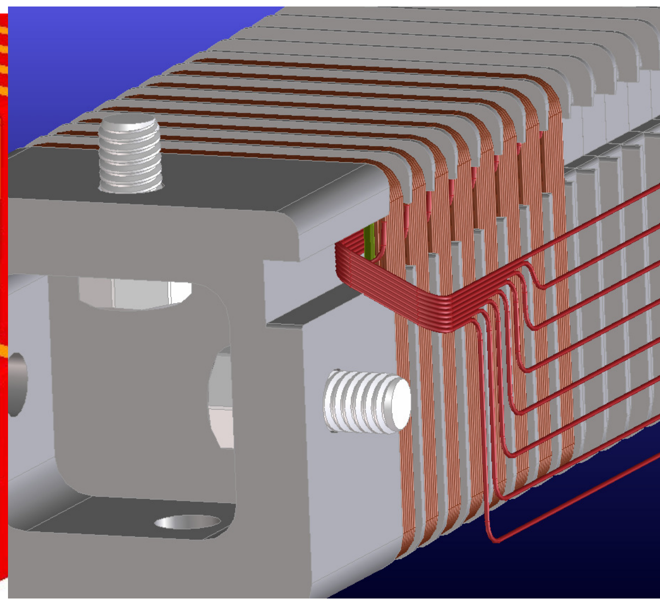
Next-generation variable polarization undulators for soft x-ray FEL's

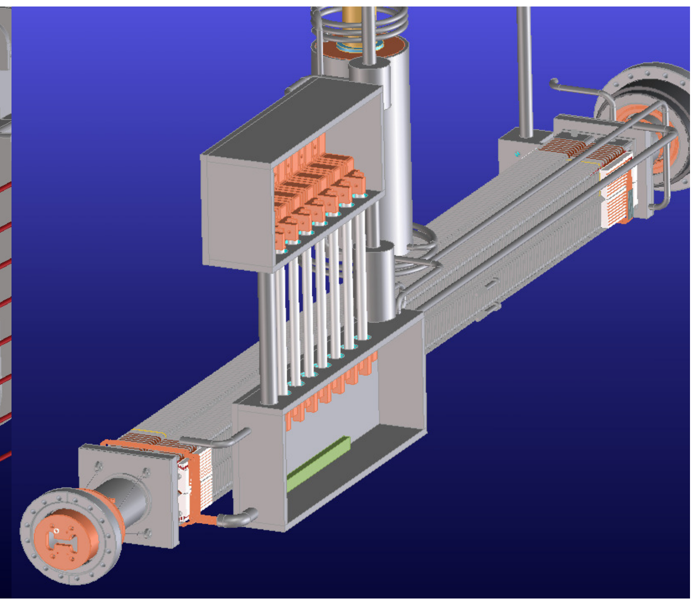
- "Traditional" approach:
  - Different methods for coil-to-coil transitions
- Can use NbTi or Nb_3Sn
  - $B_{Nb3Sn}/B_{NbTi} \sim 1.4$



- Variable polarization using a 4-quadrant array of coil-series, offset in z by $\lambda/4$ (coil series α and β)

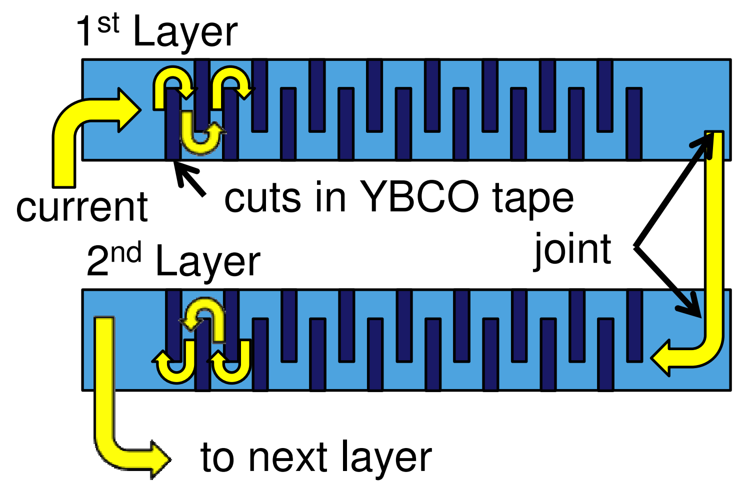


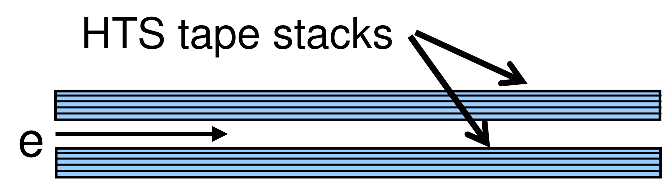


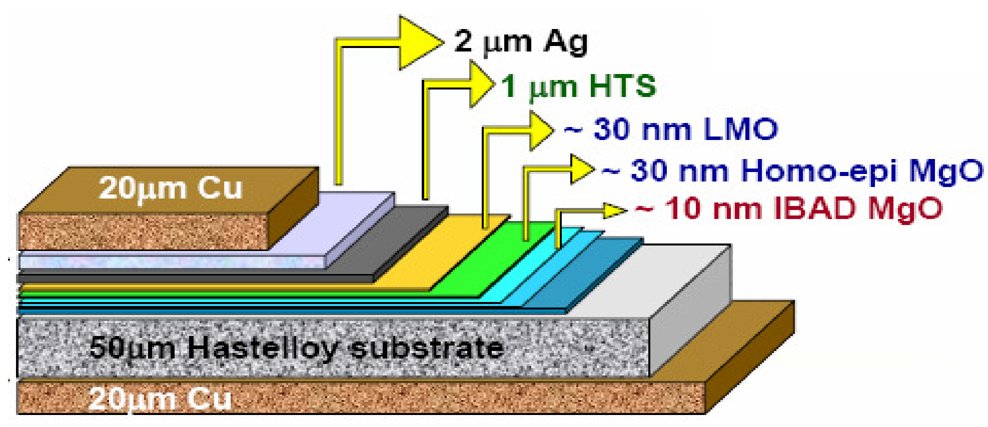


A new approach to short period undulators

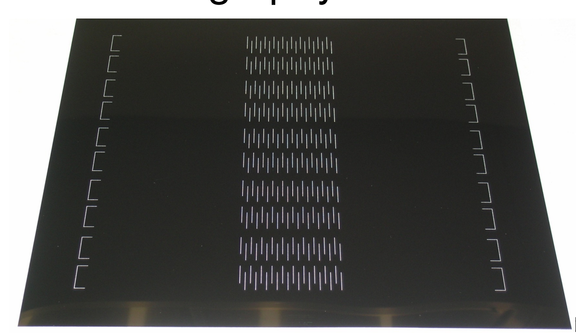
- **HTS concept:**
  - "Winding" defined by lithography
  - Use coated conductors
    - YBCO is best candidate
    - Use at 4.2K
  - ~1 micron YBCO layer carries the current
  - 12mm wide tape carries ~300A at 77K
  - factor 5-15 higher at 4.5K, depending on applied field



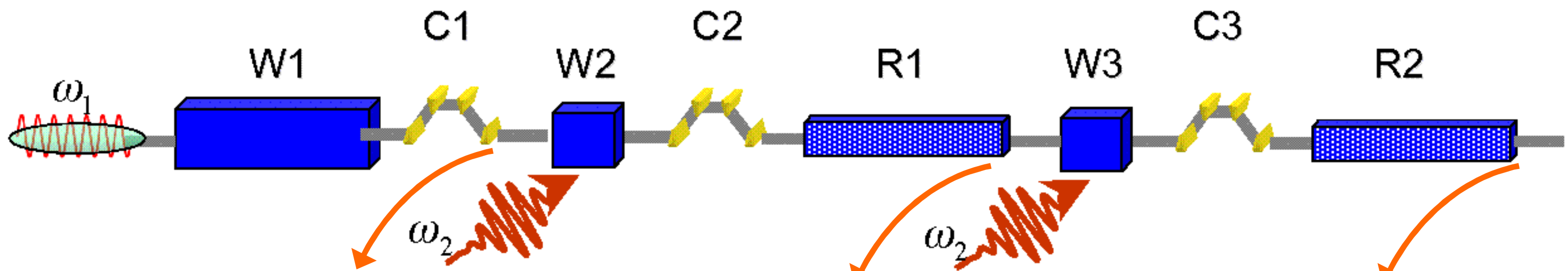


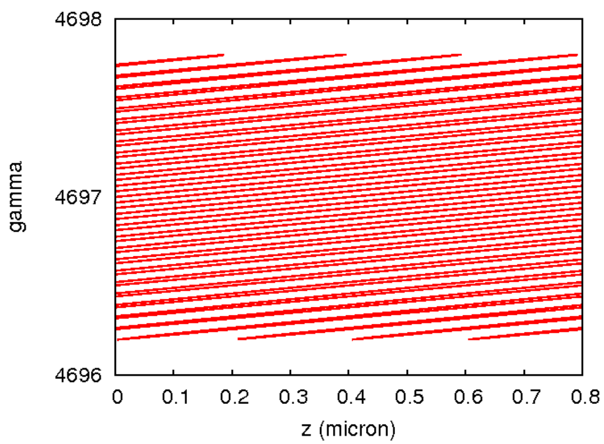


Lithography Mask

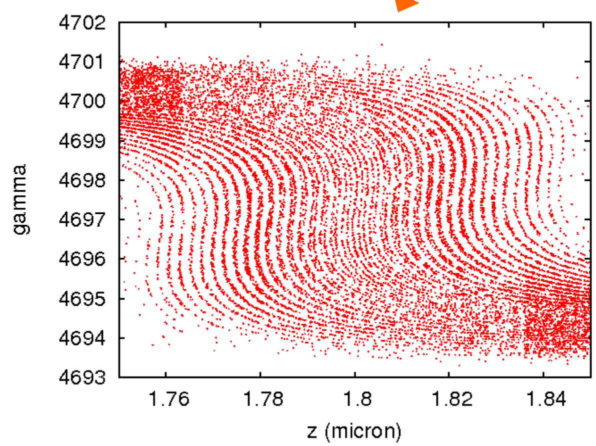


FEL design
Synchronized two-color attosecond pulses

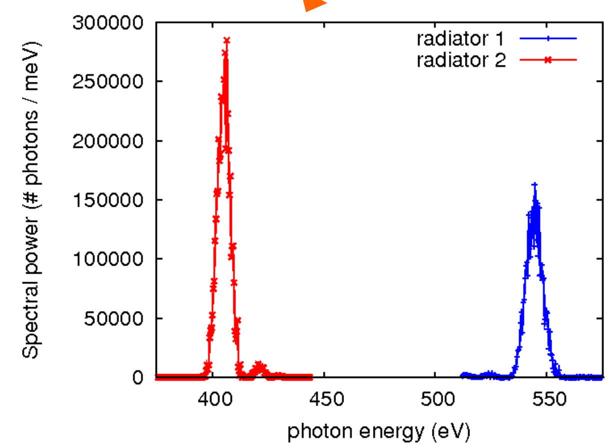




Striation in phase space



Microbunching generated at high harmonic (2–3 nm)



Output spectrum from 2 pulses

Two short pulses from one beam, distinct wavelengths

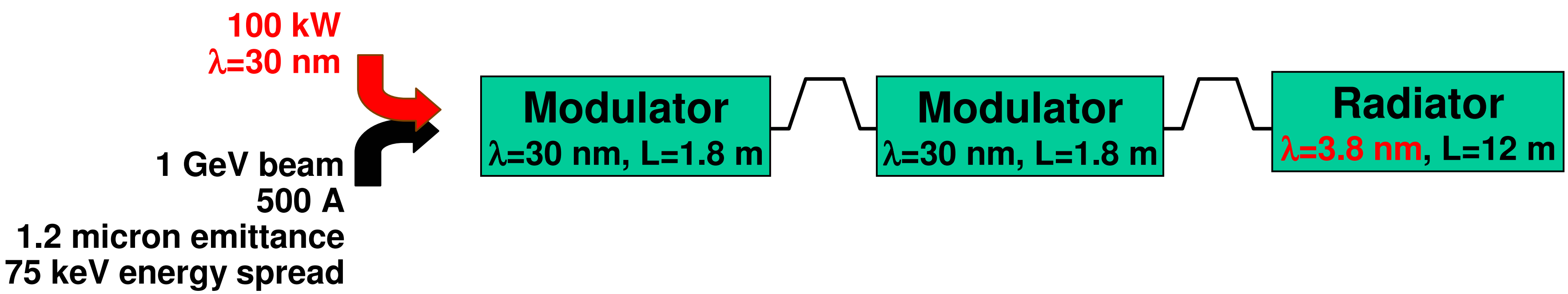
- uses EEHG scheme, both pulses share first modulation
- differential tuning by adjusting later energy modulation and chicanes

A. Zholents, G. Penn, "Obtaining two attosecond pulses for X-ray stimulated Raman spectroscopy," NIM A **612** (2010) 254.

FEL design
HHG Seeded FEL

Example with seed at 30 nm, radiating in the water window

First stages amplify low-power seed



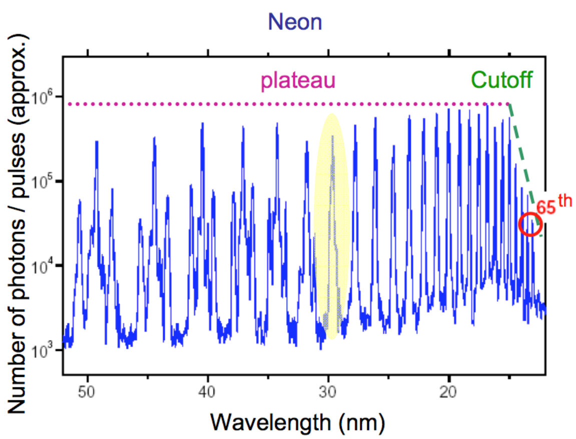
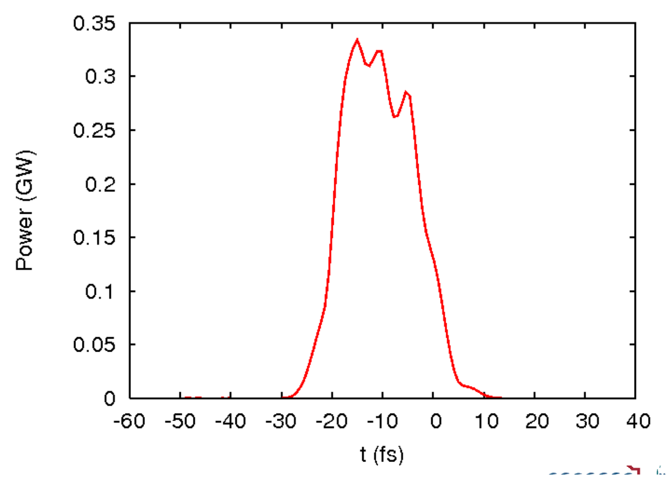


Fig. 1: High Harmonic spectrum in Ne.

300 MW output at 3.8 nm (8^{th} harmonic) from a 25 fs FWHM seed

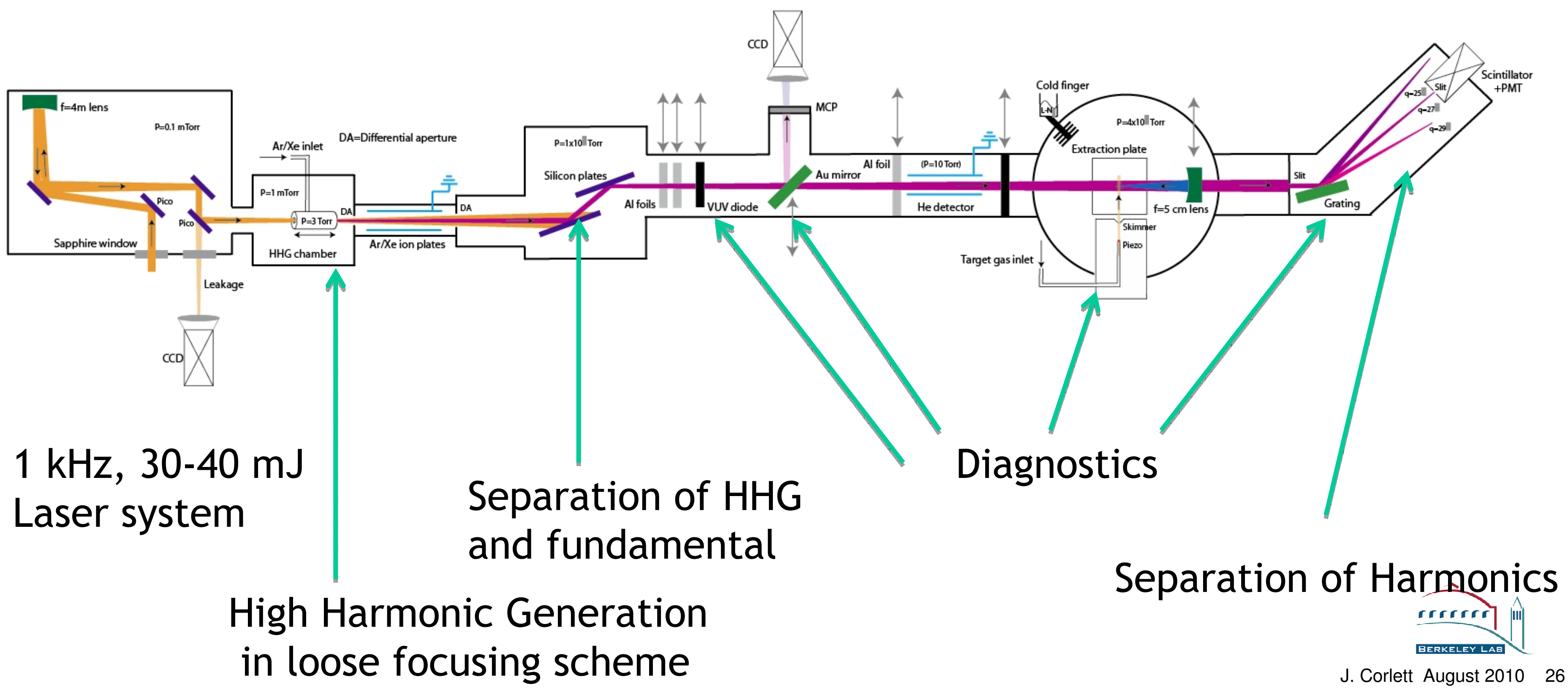


M. Gullans, G. Penn, and A.A. Zholents, "Performance study of a soft X-ray harmonic generation FEL seeded with an EUV laser pulse", *Optics Communications* 274, 167-175 (2007)

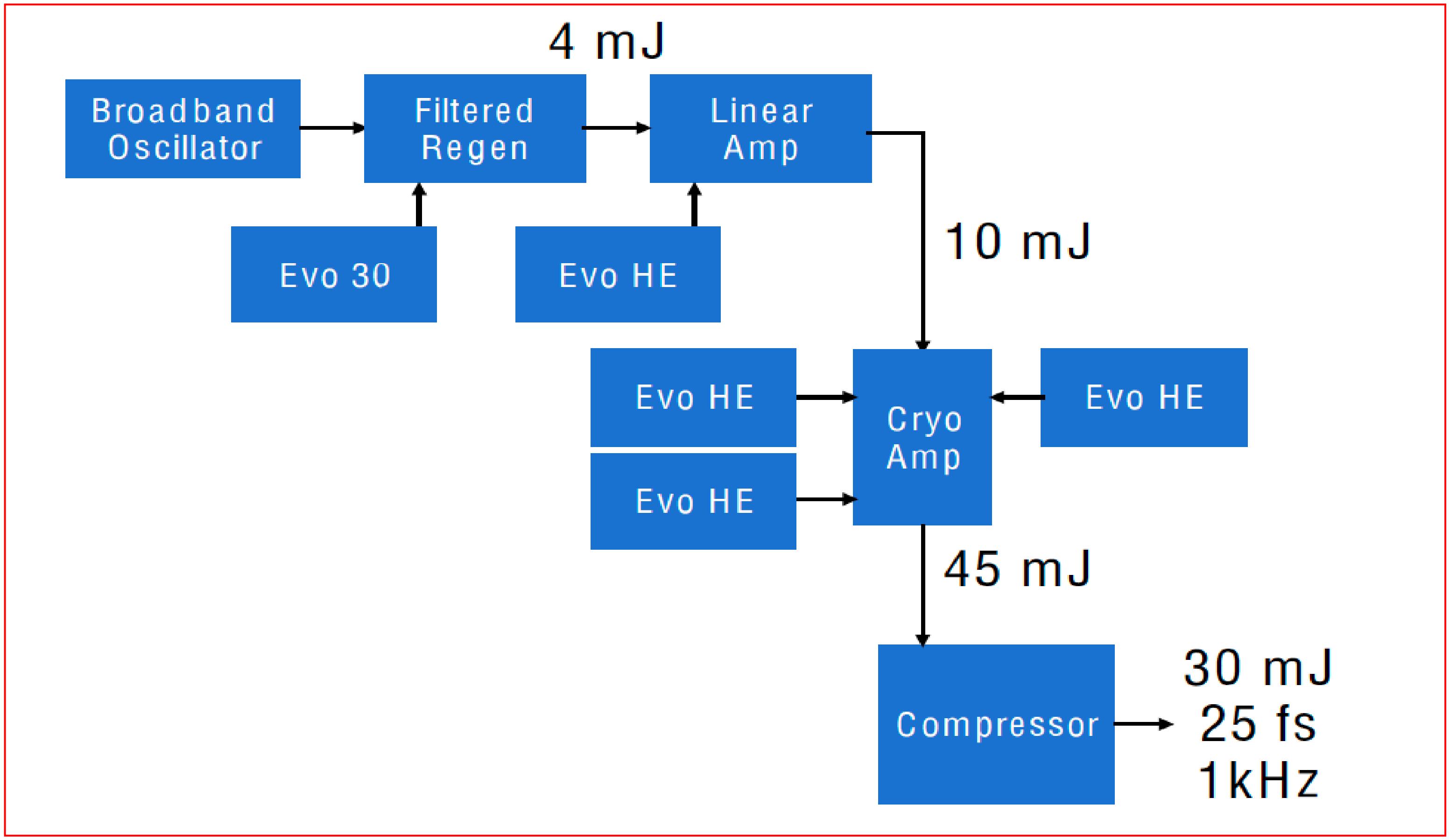
High-power HHG system

Initial challenges to be addressed

- Produce high intensities (>10^{10} photons per-pulse per-harmonic in 10-60 eV)
- Separate efficiently the HHG photon beam from fundamental
- Separate cleanly one harmonic while preserving high mode quality, beam intensity, temporal and spatial coherence
- Robust set-up with high pointing stability – critical for overlap with electron beam

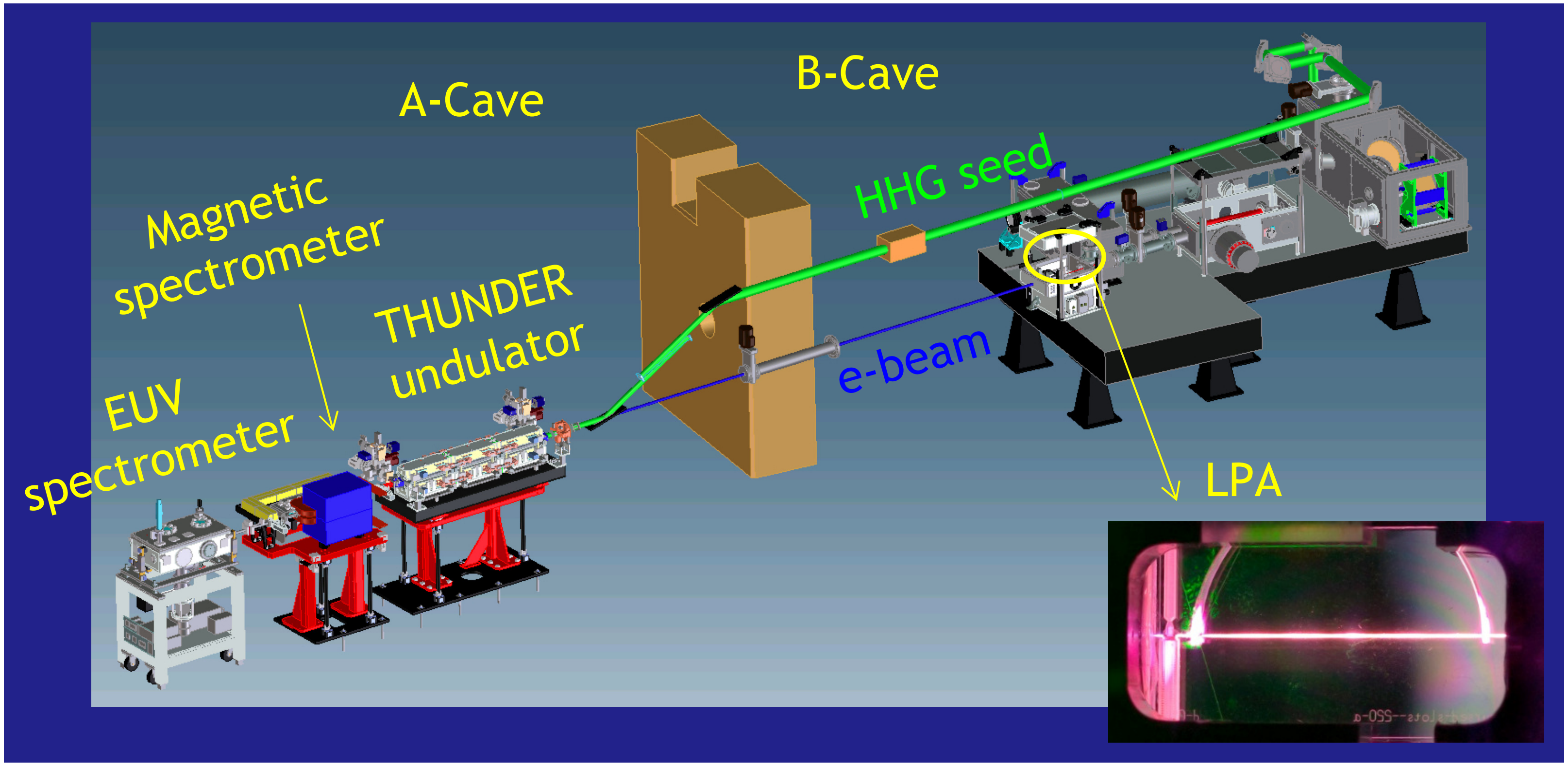


Block diagram of > 30 mJ, kHz, femtosecond laser system



75 W IR -> ~75 μW VUV

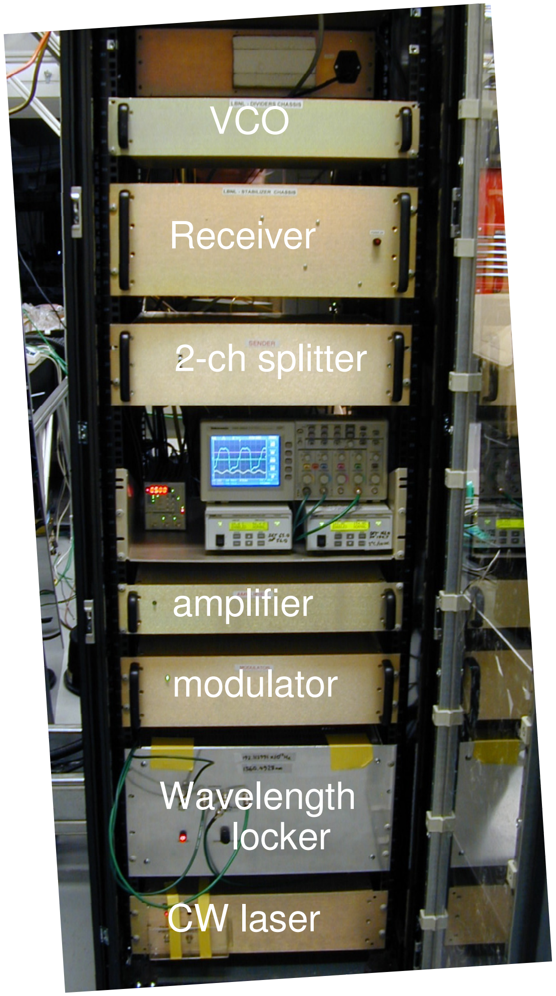
HHG seeded Laser Plasma Accelerator driven FEL



L'OASIS LPA-driven FEL

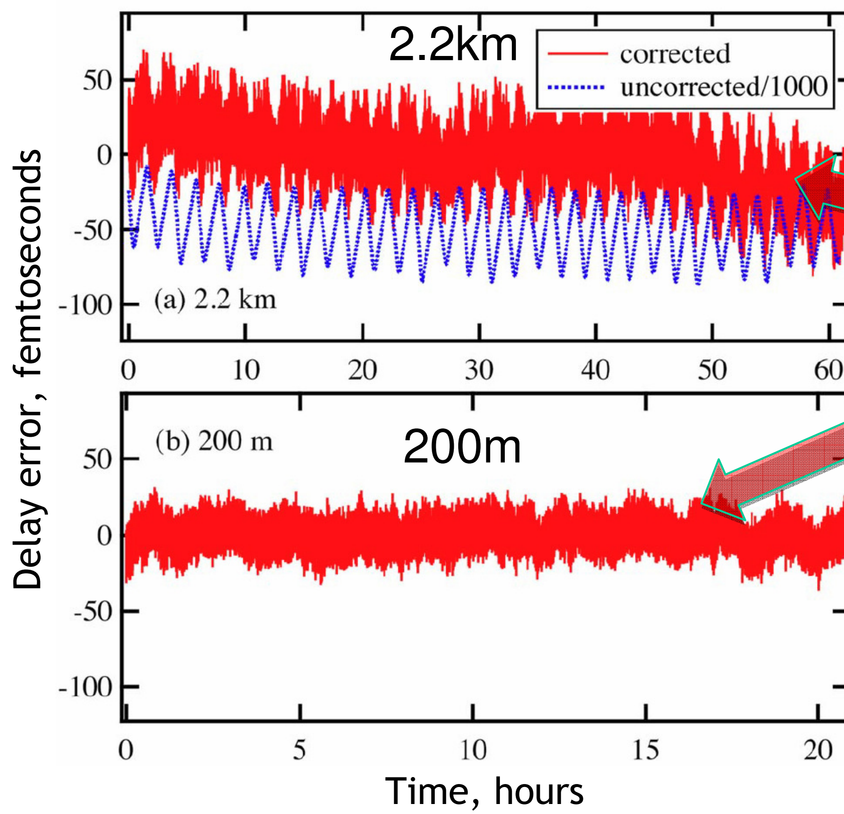
- Multi-beam synchronized laser system
- 0.5-GeV-class electrons from LPA
- Electron beam transport optics
- Undulator
- Single-shot electron & EUV diagnostics
- Know-how on HHG sources & FELs

Timing & synchronization is critical for X-ray FELs



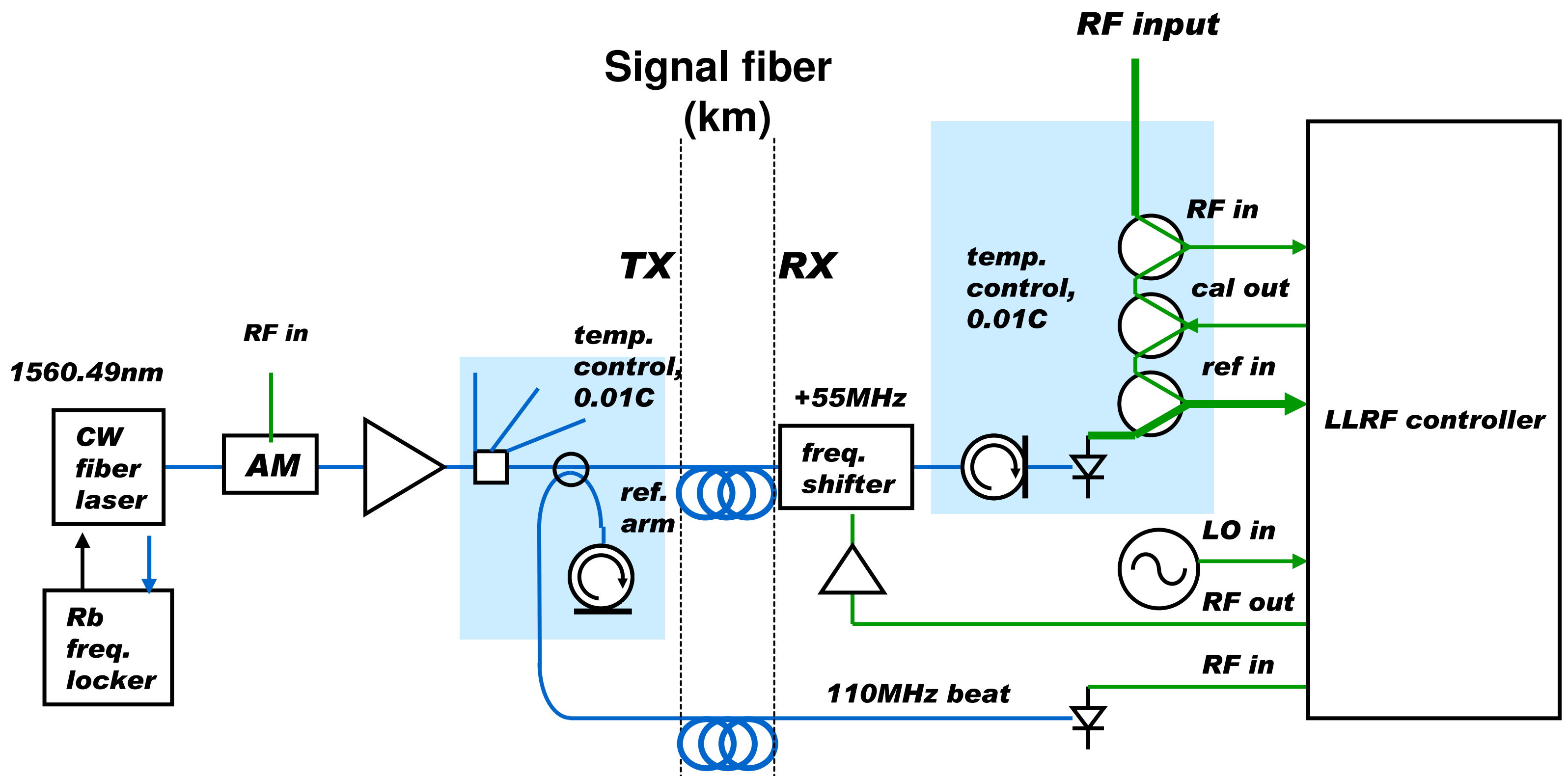
LBNL system installed in the Near End Hall at the LCLS. Planned expansion to 16 channels in 2010

- Initiated by LDRD seed funding in 2005-06, now the world leader in high precision timing for accelerator-based light sources
  - Demonstrated timing distribution over fiber links with <10 fsec stability over many days (Opt. Lett. 34, 3050 (2009))
  - Developed, built, and commissioned LCLS laser synchronization system ($2.2M) Critical component to enable first LCLS pump/probe experiment (Sept 2009)



- 1kHz bandwidth
- For 2.2km, 19fs RMS over 60 hours
- For 200m, 8.4fs RMS over 20 hours

Timing & synchronization system implementation



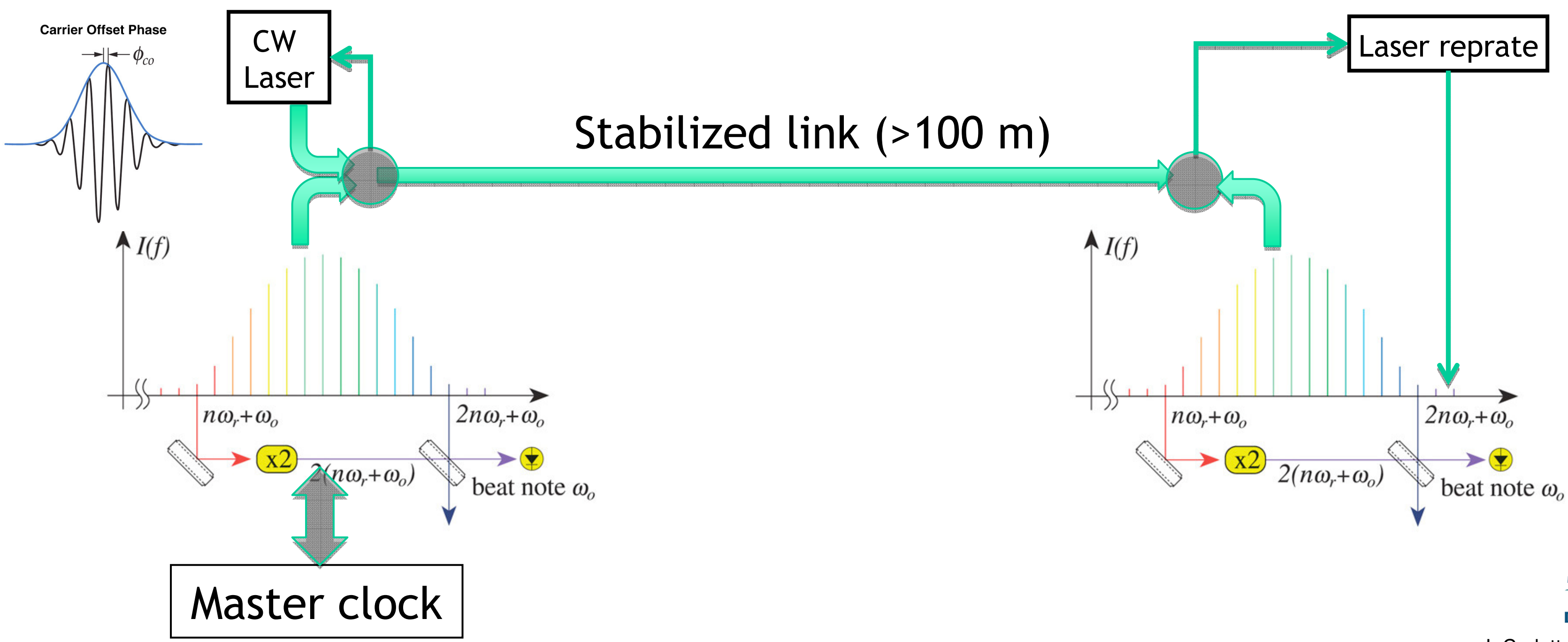
- Changes in line length are sensed by interferometer, beat signal sent to receiver (55 MHz)
- Receiver applies phase shift to frequency shifter RF, stabilizing optical phase at end
- Optical phase correction is used to calculate RF phase shift
- Thermal drift of beat fiber delay is ~1ns, becomes 0.5fs of optical phase error on main
- CW laser is absolutely stabilized
- Detection of fringes is at receiver
- Signal paths not actively stabilized are temperature controlled

Next: attosecond timing

- LCLS demonstrates <10 fsec electron and x-ray pulses
- Future seeded FEL experiments will have sub-fsec requirements on laser/laser synchronization

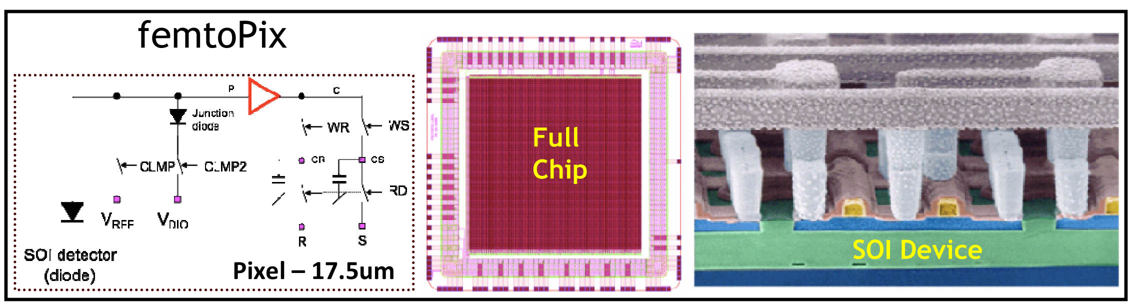
Concept:

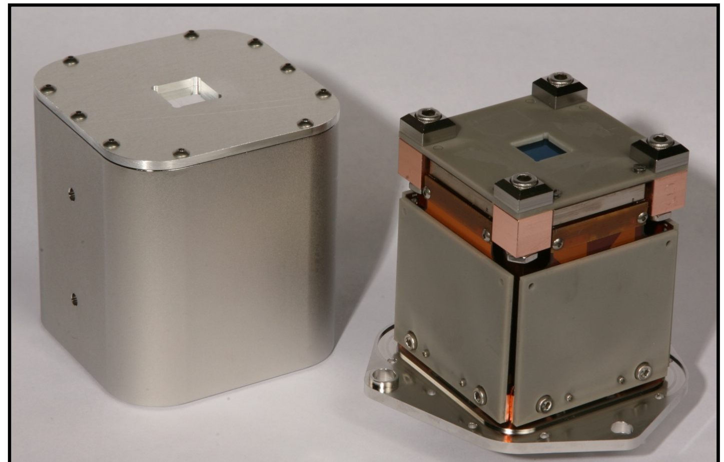
- Attosecond experiments will use carrier envelope phase stabilized lasers
- Lock the same harmonic in each laser
- Stabilize the link between the two lasers and the two lasers will be synchronized

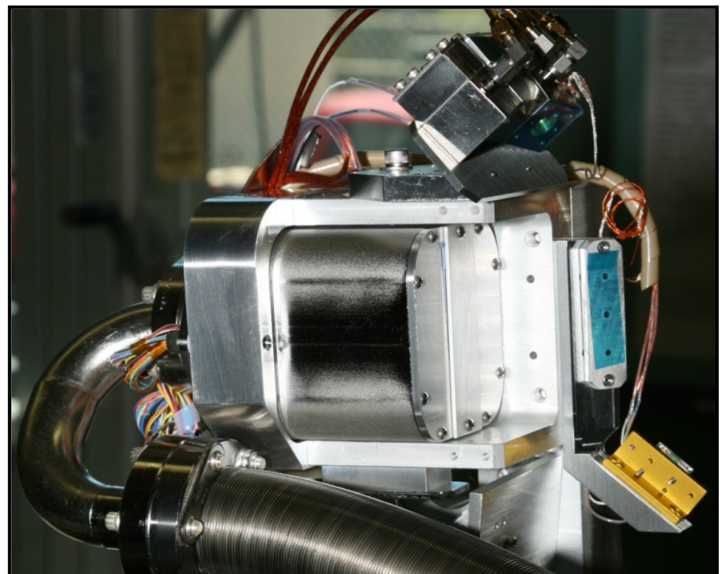


Path to Higher Detector Readout Speeds

- High Speed Readout Roadmap
  - Today: 200 fps
    - FastCCD (FCCD) and compact FastCCD (cFCCD)
  - Tomorrow: 4,000 fps
    - “femtoPix” - Silicon-on-Insulator (SOI) Detector
      - Femto second time resolution
      - Performance results late 2010
  - Day after tomorrow: 10,000 fps
    - Very FastCCD (VFCCD) – Fully implemented column parallel CCD
    - Hardware development only
  - NGLS Grand Opening: 100,000 fps
    - NGLS CCD – VFCCD integrated with on-chip signal processing



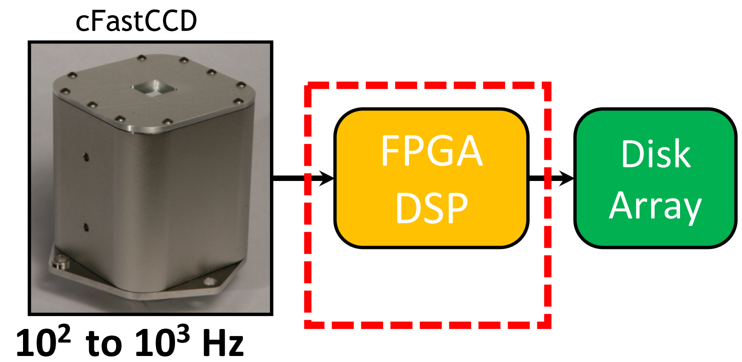

cFCCD Camera Head Assembly


cFCCD Camera mounted to LCLS ready mechanics

How we get there from here

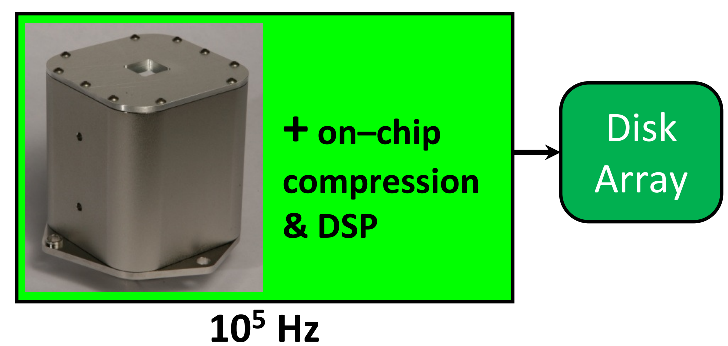
Performance Demonstration

- "Outside" Implementation
  - Implement real-time data compression "outside" of the CCD detector using Field Programmable Gate Arrays (FPGA) in-line between the Detector and Data Acquisition System
    - Proves algorithm performance
    - Demonstrates clearly the limitations of moving data off chip at required speeds

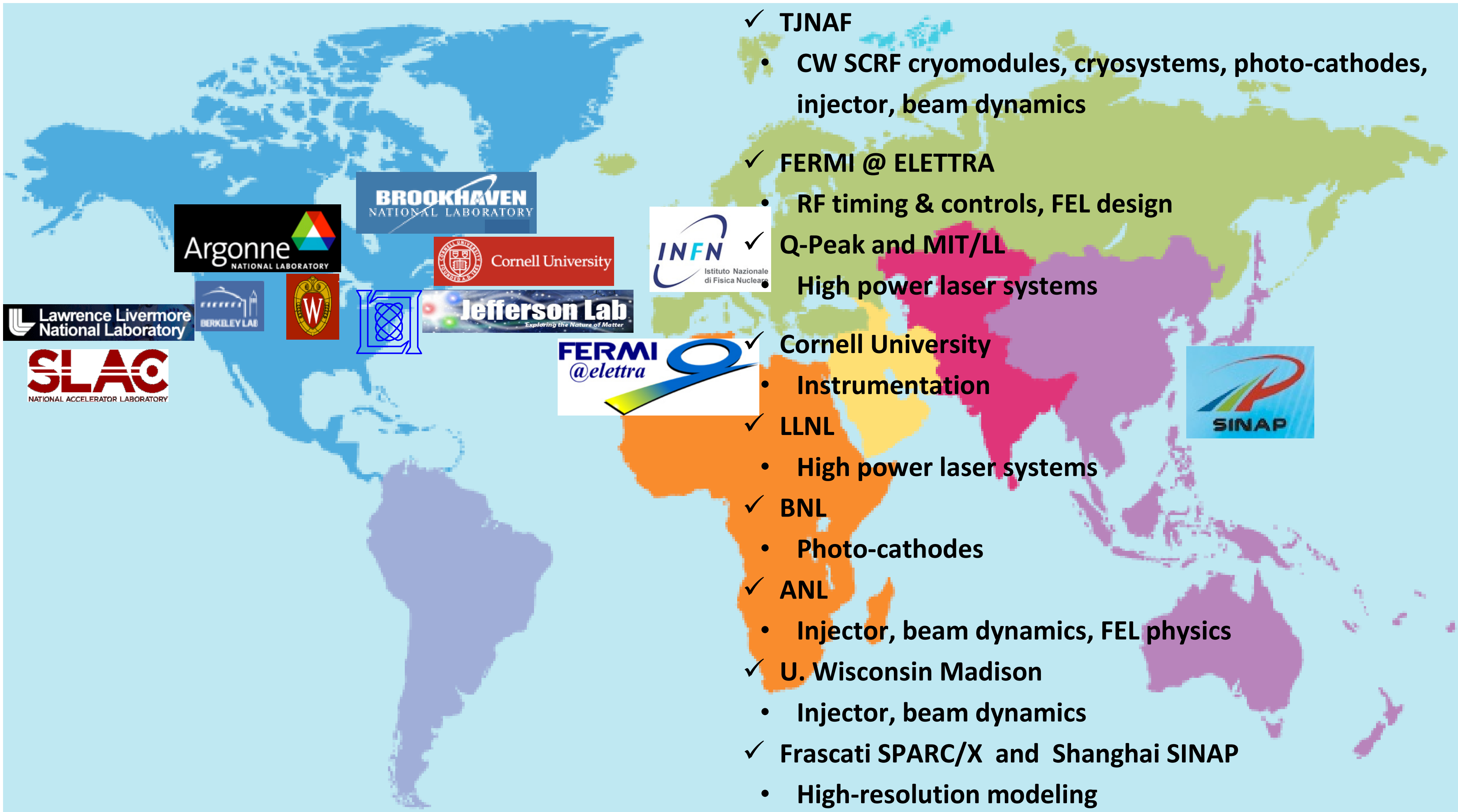


Future Development

- "Inside" Implementation
  - Demonstrate that the algorithms can be implemented on the same silicon as the detector
    - e.g. Cell phone cameras compress full images into JPEG files
    - Cell phone cameras = $5B/year industry



Accelerator R&D Collaborations



- **Current activities:**
  - ✓ **SLAC / LCLS**
    - **Photo-cathodes, ECHO-7, LCLS-II FEL design, timing & synchronization, soft x-ray science**
  - ✓ **TJNAF**
    - **CW SCRF cryomodules, cryosystems, photo-cathodes, injector, beam dynamics**
  - ✓ **FERMI @ ELETTRA**
    - **RF timing & controls, FEL design**
  - ✓ **Q-Peak and MIT/LL**
    - **High power laser systems**
  - ✓ **Cornell University**
    - **Instrumentation**
  - ✓ **LLNL**
    - **High power laser systems**
  - ✓ **BNL**
    - **Photo-cathodes**
  - ✓ **ANL**
    - **Injector, beam dynamics, FEL physics**
  - ✓ **U. Wisconsin Madison**
    - **Injector, beam dynamics**
  - ✓ **Frascati SPARC/X and Shanghai SINAP**
    - **High-resolution modeling**

Thanks to an Excellent Team
Contributions From Many Divisions Within LBNL

Ken Baptiste
Walter Barry
Ali Belkacem
John Byrd
Andrew Charman
John Corlett
Woody Delp
Peter Denes
Rick Donahue
Larry Doolittle
Roger Falcone
Bill Fawley
Jun Feng
Daniele Filippetto
Stefan Finsterle
Jim Floyd
Steve Gourlay
Mike Greaves
Joe Harkins
Zahid Hussein
Preston Jordan
Janos Kirz
Eugene Kur
Slawomir Kwiatkowski
Steve Leone
Derun Li
Steve Lidia
Tak Pui Lou
Bill McCurdy
Pat Oddone
Howard Padmore
Christos Papadopoulos
Gregg Penn
Paul Preuss
Ji Qiang
Alex Ratti
Matthias Reinsch
David Robin
Kem Robinson
Glenna Rogers
Fernando Sannibale
Richard Sextro
Bob Schoenlein
John Staples
Christoph Steier
Theodore Vecchione
Will Waldron
Weishi Wan
Russell Wells
Russell Wilcox
Jonathan Wurtele
Lingyun Yang (BNL)
Sasha Zholents (ANL)
Max Zolotorev